ON-LINE CONTROL OF MACHINE TOOL VIBRATION DURING TURNING OPERATION

by

M. S. SHARATH

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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M. S. SHARATH

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Dedicated to

My Grand Father

Certificate

This is to certify that the thesis entitled, "On-Line Control of Machine Tool Vibration during Turning Operation" by Sharath, M.S., Roll No. 8620537, is a record of work carried out under my supervision and has not been submitted elsewhere for a degree.

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S.K. Chaudhury
Assistant Professor
Department of Mechanical Engineering
Indian Institute of Technology
Kanpur

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Abstract

Machine tool Chatter is one of the major factors for limiting the performance of the machine tool. Much attention has been focussed on minimizing this problem either by improving the dynamic compliance of the structure or by selecting the cutting conditions such that Chatter does not occur. Limiting the cutting conditions leads to a lower production rate.

Machine tool Chatter is bound to affect surface finish and dimensional accuracy. The surface roughness is governed by the relative displacement between the tool and the workpiece. As this relative displacement directly affects the depth of cut, in principle if this depth of cut variations are prevented or reduced, the surface finish should improve.

In this thesis an attempt has been made to design a control system which will reduce variations in the depth of cut and hence improve surface finish during turning operation in a centre lathe. The control system consists of an optical sensor to measure relative displacement between the tool and the workpiece and a tool actuator to reduce this relative displacement. The sensor consisting of an ordinary bulb as a light source, bifurcated optical fibres for transmitting light to and from the workpiece surface and a phototransistor

set-up, achieved a high resolution of 1μm. The sensitivity was as high as 2.206 mV/μm for a cylindrical surface having a surface roughness value of 11.5μm. The sensor has a wide working range of about 1.1 mms (within 2.5% linearity) and sufficient reliability for specific research purposes. The tool actuator was designed to hold as well as excite the tool by vibrating the same along the radial direction. The sensor probe was positioned beside the tool. The tool actuator, based on electromagnetic principle, has some distinctive features in its performance, such as a frequency range of 10 to 400 Hz and a peak-to-peak amplitude upto 100μms.

The principle, verified by experimental results, indicated improvements in surface finish for different cutting conditions and parameters.

The improvement in surface finish was shown by measuring two identical surfaces machined without and with feedback control. Comparing the amplitudes of vibration without and with feedback control by a socalled amplitude reduction ratio was determined, which has the maximum value of 1.33. Experimental results show 22% improvement in surface finish.

Chapter 1

Introduction

1.1 Introduction

Most of the research studies in the field of adaptive control of machine tools have been carried out with the main objective of either increasing production rate or reducing cost. The parameters to be controlled are cutting force, spindle torque, tool wear, temperature in the cutting zone etc.[1] . Efforts have been made to develop algorithms to relate these parameters to a predefined performance index and then control the performance index by varying either speed or feed rates or both of a machine tool, with reasonable success[2]. Attempts to improve surface finish by adaptive control system have been considered only in the recent past[3]. This is basically due to the lack of reliable sensors.

Machine tool chatter is considered to be one of the main reasons for the detrimental surface finish. Chatter is recognized as one of the primary performance index of a machine tool. Chatter is undesirable because of its adverse effects on surface finish, machining accuracy and tool life. Furthermore, Chatter is also responsible for lower production rate because, if no solution to eliminate Chatter can be found, material removal rates have to be lowered until

vibration free performance is obtained. Ofcourse, Chatter is not the only vibration phenomenon occurring under practical conditions. Free vibration (induced by shock) and forced vibration (induced by unbalance effects, gear and bearing errors, etc.) either arising in the machine itself or transmitted through the foundation from other machines are frequently encountered and are difficult to avoid. However, as soon as the causes responsible for free or forced vibration have been identified, it is always possible to find methods of eliminating them. The physical causes underlying the mechanism of Chatter are not fully understood and this is why it is so often extremely difficult to find any solution to eliminate them. In addition, Chatter is so inconsistent that the tendency of a machine to exhibit Chatter is often observed in the developing stage. The most important characteristic property of Chatter vibration is that it is not induced by external periodic forces, but rather maintained and generated in the vibratory process itself[18].

In the following section a detailed review of relevant works carried out in the field of machine tool Chatter as well as on-line measurement and control of machine tool performance is presented.

1.2 Review of the Previous Work

Ledergerber[4] has dealt with the basic considerations which have led to the development of control systems

allowing more automation of machining cycle. He has also described a new adaptive control system for turning operation with preselected speed. Only the feed rate is varied with torque of the spindle as a performance index. It is also shown that by employing adaptive control for turning operations economical advantage can be achieved.

A Galip Ulsoy, Yoram Koren and Fred Rasmussen(3) have listed the principal developments in the field of adaptive control over the past two decades. Some of the reasons for insufficient progress in the field of adaptive control have been listed as lack of development of reliable sensors and stable-parameter-adaptive-control strategies.

Slavko M. Arvoski(5) presents a survey of developed wear sensors for adaptive control systems of machine tools. Sensors based on pneumatic principle, capacitive principle, cutting resistance and optical principle have been discussed in detail. It has also been shown that optical principle has the best sensitivity, accuracy and reliability for measuring discontinuous wear of tool. A new sensor based on the measurement of the radioactivity of activated cutting elements of the tool during cutting has been presented.

Potential non contact optical methods for in-process surface roughness measurements have been described by K. Mitsui(6). The methods include reflected light position detection and focus error detection. These methods are

described while using fibre optics and optical lever and have been applied for grinding. Swarf and cutting fluid are shown to hamper the accuracy of measurement. Methods to overcome them or protect the optical instruments from them have not been discussed.

Experimental investigation of a technique for the measurement of surface roughness using fibre-optics has been briefed by W.P.T. North and A.V. Agarwal[7]. A pair of fibre optic bundles of similar specifications are used to carry both the incident light to and the reflected light from the object surface at different angles of incidence. A good correlation has been shown to exist between the average roughness of the object surface and the measured reflected light. The best angles have been found to be 0° and 35° from surface normal. A graph of percentage of maximum output and the distance between the probe and the reflecting surface (Fig. 1.1) shows that maximum output is found at distances between 0.14" and 0.3". The reflected surface used is a static flat plate. The variation of the reflected output for curved surfaces have not been shown.

A. Novak/B. Colding[8] have presented an electro-optical method by using He-Ne laser for non-contact dimensional measurement. It has been stated that the

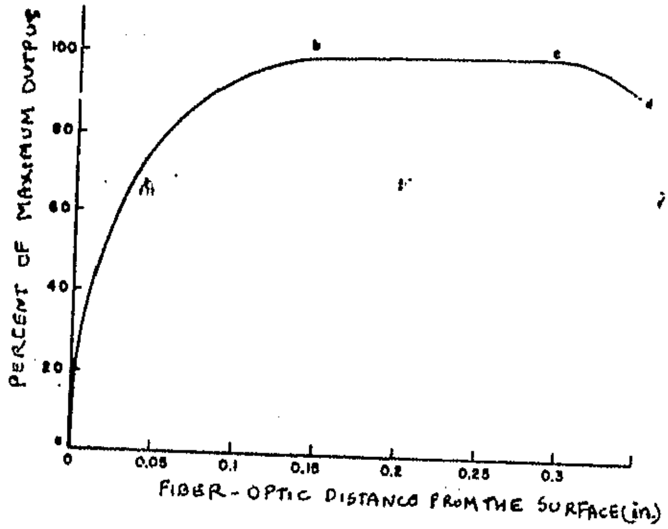


Fig. 1.1 Response Characteristic curve

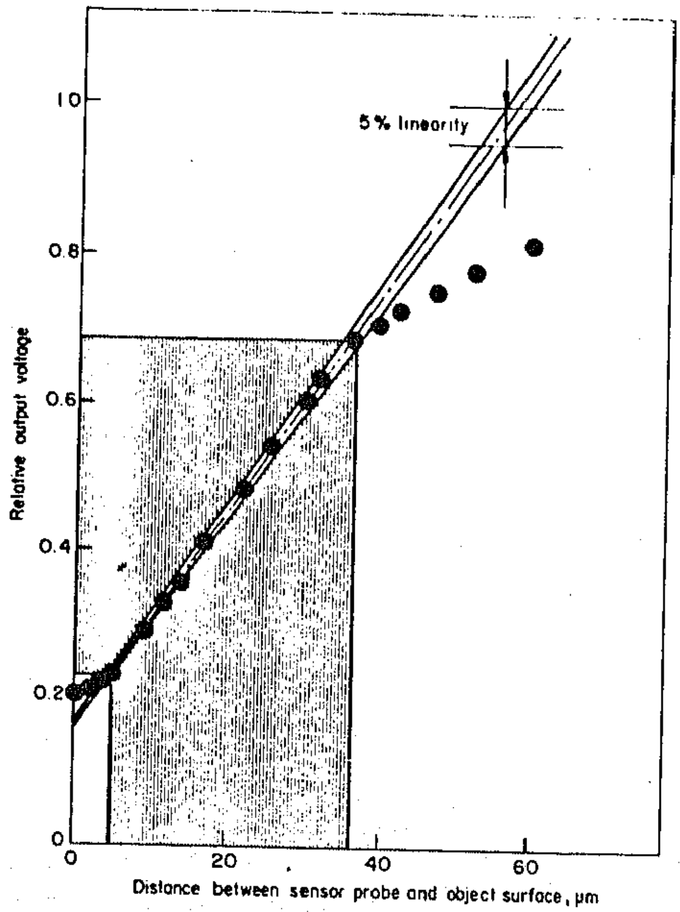


Fig. 1.2 Best linearity range

the sensitivity of the device as 5 mV/0.001 mm, repeatability as 0.002 to 0.003 mm and accuracy as 0.01 mm. The maximum diameter of the workpiece on Lathe has been limited to 280 mm. Again the basic problem in this method is to position the photodetector at an angle which gives the maximum output. Vibrations in the machine are found to change the angle of the photodetector which will affect the accuracy of the measurement.

N. Ikawa, S. Shimada and H. Morooka[9] have described a photoelectronic displacement sensor consisting of a 50W light source, optical fibre bundles for transmission of the illuminating and the reflected light and photo-diode set-up. A high resolution of 0.5 nm and a stability of 1 nm in 20 seconds has been achieved . The frequency has been limited to 1.6 KHz. As seen in the graph (Fig. 1.2) the best linearity is when the distance between the fibres and the reflecting surface is between 7 μm and 20 μm (around 5% linearity).

It has not been mentioned as to where the photodiode detects maximum intensity of power. The calibration curve has been stopped at 60 μm. The nature of the curve beyond 60μ m has not been shown. So close a distance as 30μ m might damage the probe surface, if the workpiece surface has a poor surface finish. The probe has been

calibrated only for flat surfaces. The effect of the probe for measuring cylindrical surfaces has not been discussed.

A drift in the sensor has been noted for nominally no displacement. This is due to thermal deformation of the light source set-up by the generated heat. This may be due to the high capacity bulb (50W) used as a light source.

Double laser beams with continuous pursuits of a workpiece axis on a NC machine have been used by M. Shiraishi[10]. The laser beam diameter used was about 2μm. The main problem is to focus the beam at a point and then detecting the reflections. Disturbances such as chips and cutting fluid were eliminated by air-blast principles.

T.L. Subramaniam, M.E. Devries and S.M. Wu[11] have suggested a stochastic method for detection, prediction and control of machining Chatter by a computer. The effect of speed and feed on Chatter have been considered. Then Chatter is controlled by varying feed and speed. However they have considered the vibration level of the tool holder whereas it is well known that the relative motion between the tool and the workpiece is the parameter which affects Chatter.

B.M. Bazrov[12] has investigated as to how machining accuracy is improved by controlling elastic displacements. This is done by controlling the relative motion of the tool cutting edges and workpiece locating faces. It is necessary to stabilize the ratio of the force causing elastic displacement and the stiffness of machine-fixture-workpiece-system. Three methods for reducing machining error have been suggested:

(i) Introducing a correction to the static setting dimension.

(ii) Stabilizing the dynamic setting dimension by introducing a correction constantly.

(iii) Combined method by controlling feed rates and depth of cut within a specified range. Control algorithms are described for the latter method.

N.F. Shillam[2] has described a practical method for varying machining speeds and feeds by the direct feedback of cutting conditions. Temperature at the cutting zone is considered as an index of machining. With this system cutting speed is varied keeping the feed constant. Another system used is by controlling thrust force variations by equivalent feed rate variations so that higher metal removal rate can be achieved. This method gives automatic

protection to the tool by keeping the forces on the tool constant. Better results are achieved with both the systems combined. The main drawback of this method is that the temperature at the cutting zone increases with increasing tool wear. Hence, speed decreases with time and so metal removal rate reduces. This method shows an increase in metal removal rate by 30% during facing operation.

M. Shiraishi/K. Uehara(13) have dealt with a non-contact measuring apparatus of workpiece dimension and the in-process control utilizing the apparatus on a NC lathe. The measuring principle is by a laser unit, photoconductive cells and optical systems. The errors have been suppressed to within a tolerance limit of $\pm$ 10 μm. The errors in the dimension are corrected with positioning motors when the surface roughness exceeds the limit of $\pm$ 10μm. The diametral change of workpiece along the length is shown in the Fig. 1.3. It is seen from the figure that there is a predominant size drift towards the chuck end. This might probably be due to the tool wear and thermal deformation of the tool. It is also seen in the figure that instantaneous correction is done when the tolerance crosses the limit of $\pm$ 10μm. This may be one of the reasons for not achieving accuracies better than that achieved.

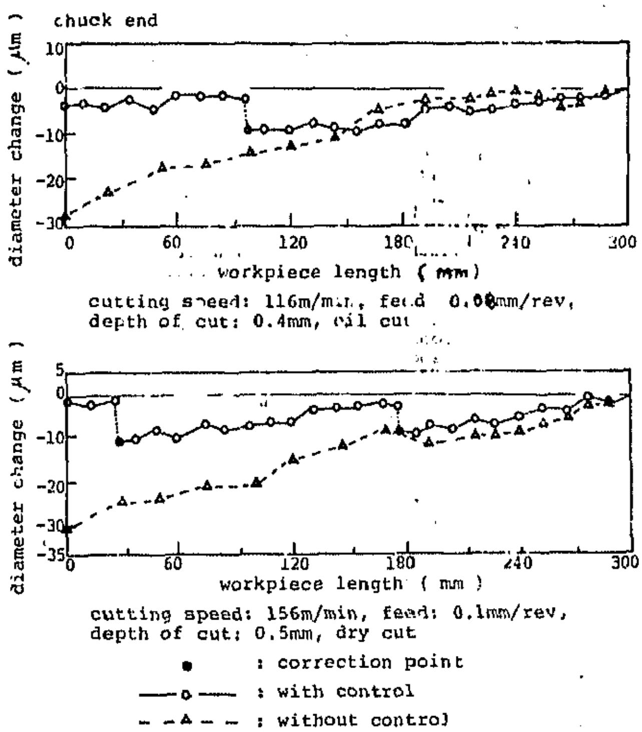


Fig. 1.3 An example of workpiece diameter change

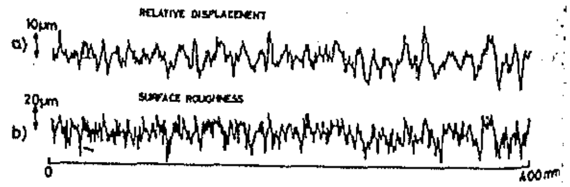


FIG 1.4 Waveforms of the Relative Displacement and the Surface Roughness (S45C, Cutting Speed : 40 m/min)

WORK MATERIAL	WORK DIAMETER	CUTTING SPEED	SPINDLE SPEED	FEED	DEPTH OF CUT
BRASS	70 mm	20 m/min.	91 rpm	1 mm/rev.	0.2 mm
CARBON STEEL	72	40	177	1	0.3
CARBON STEEL	72	60	265	1	0.3
CARBON STEEL	72	80	354	1	0.3
CARBON STEEL	72	100	442	1	0.3
CARBON STEEL	72	120	531	1	0.3

Table. 1.1 Cutting Conditions for the Analysis

Cross spectrum analysis is applied to the relation between the relative displacement of the tool to the workpiece and the surface roughness by K.Mitsui, H. Sato and N. Takenaka[14]. The surface roughness is measured by using laser beam and photodiode array. The resolution of the system being 2μm. The relative displacement being measured by a displacement sensor. The analysis is shown in Fig. 1.4.The experiments were conducted on a Lathe.

The cross spectrum analysis makes it obvious that the gain of the surface roughness to the relative displacement is estimated as 1.0 with high coherency for frequencies less than 200 Hz. In this experimental set-up the tool is excited by an electro-hydrautic exciter by a random signal. The drawbacks of such an arrangement are that the displacement of the tool is measured whereas it is the relative displacement between the tool and the workpiece which is related to the surface roughness. The coherency may be due to the fact that the tool is being excited randomly and the displacement sensor, which is attached to the tool, traces the same path. If the surface roughness of the workpiece is within the excited range of the exciter, then the surface roughness may match the displacement level of the tool especially when the cutting conditions (as in

this case) are such that Chatter does not occur. The cutting conditions used for the analysis are shown in Table 1.1.

C.L. Nachtigal and N.H. Cook[15] have proved that active control of machine-tool Chatter applied to an engine lathe indicated significant improvements in production rate, in transient response and in static stiffness. An analysis of both uncontrolled system and controlled system have been dealt. A control signal from strain gauges consisting of a measure of the cutting force was used for controlling the machining process. The tool servo consisted of a electrohydraulic actuator bearing against a tool holder mounted on steel disk springs. In order to hold the tool rigid the stiffness of the springs was designed to be several times greater than that of the workpiece. But the large spring load, as seen by the actuator, limits its performance. It has also been found that the system was stable over a wide range of cutting width, with lower gain. It has been suggested to replace the tool-holder springs with an active tool position feedback loop.

C. Nachtigal[16] has presented the design basis for a force feedback Chatter control system, including both analytical and experimental considerations,

From frequency considerations, the tool itself has to be actuated in response to Chatter. An electrohydraulic servo actuator has been used. Strain gauges mounted on the tool have been used to measure the cutting force. This particular system would be applicable only when the machine and workpiece resonant frequencies are reasonably well known and constant. The system has been proved to be stable at lower Chatter modes only.

The effect of relative vibrations in the radial direction on the tool life have been considered by A.L.Vilson et al[17]. It has been shown that machining with a vibrating tool improves the life of the tool. All experiments have been conducted on a Lathe. An electromagnetic vibrator has been used for vibrating the tool. To maintain the set vibration frequency and amplitude feedback is done in the circuit. The relative vibration span (peak to peak amplitude) has been varied from 2 to 160 μm with a frequency of 380 Hz. It has been assumed that vibration frequency within the range of 40 to 400 Hz does not significantly affect tool life. The tests have shown that for vibration span less than 40 μm, the tool life has increased. For vibration spans greater than 60 μm, the wear of the tool has increased. It has been suggested to keep the vibration level below 40 μm in order to improve tool life.

1.3 Objectives and Scope of the Present Work

The present work is in the field of machine-tool Chatter. In the past much attention has been focussed on minimizing Chatter by improving the dynamic compliance of the structure. These approaches have been of a passive nature, such as increasing the structural damping, increasing the rigidity, addition of a vibration absorber, etc. The present work involves on-line control of Chatter in a centre Lathe during turning operation to achieve better accuracy and surface finish. The objectives of the present work can be briefly mentioned as the following:

(i) Design of a sensing device to sense Chatter during machining of workpieces.

(ii) Design of a tool actuator to constantly position the tool in real time.

(iii) Design of a feedback control system to control the Chatter occurring during machining.

In addition, the control system is to be tested on a centre lathe and verified by experimental results.

One of the major difficulties of an active Chatter control system is the selection of a sensor. The signal from the sensor must contain information about all the vibrational modes. Since the relative

displacement between the tool and the workpiece being machined determines the Chatter amplitude, the sensor should be capable of transmitting signals proportional to the distance between the sensor probe and the workpiece. In addition, the sensor should be reliable and accurate and sense vibrations in real time. Sensors based on various principles such as capacitive principle, pneuamtic principle, cutting resistance and optical principle etc. have been used in the past. The one which has been widely accepted to have the best sensitivity, accuracy and reliability and used more often (6,7,8,9,10,13,14) is the sensor based on optical principle. In most of the sensors based on optical principle Laser has been used successfully (8,10,13,14). But the basic problem of using a Laser is focussing and detection of the Laser beam. An ordinary 50W bulb has been used successfully in (9). The photoelectronic displacement sensor consisting of a 50W light bulb, optical fibre bundles for transmission of the illuminating and the reflected light and a photo-diode setup used in (9) seems to have a very high resolution of 0.5 nanometer. The sensor set up is economical. The only drawback of this sensor is the drift of the sensor. But as pointed out in the earlier section this may be due to the high wattage bulb used. The high resolution achieved with this sensor set up is possible only when the following conditions hold true.

(a) The workpiece (or the reflecting surface) is flat.

(b) Two similar sensor setups, i.e. a light source, optical fibre bundles and photodiode, are at the same distances from their reflecting surfaces so that the initial output which is the difference of the photo voltages is zero. One of the sensor setup is fixed as a reference.

But the conditions that exist during turning operations on a Lathe are entirely different from that which are listed above. The workpiece will be having a cylindrical surface. Also, it is extremely difficult to set a reference set-up which is always stationary. This reference set-up can be replaced by a reference voltage and the output from the differential amplifier will be a measure of relative vibrations. The block diagram of the sensing circuit is as shown in Fig. 1.5.

A dimensional control of the workpiece has to be done in real-time. As soon as relative vibrations between the tool and the workpiece, normal to the machined surface, is detected, the vibrations have to be suppressed before it stabilizes. Chatter vibrations occurring in any machine is due to the variations in the magnitude of the forces acting on the cutting tool. These forces acting on the cutting tool are functions of feed rate, cutting speed and depth of cut, under steady state cutting conditions. But in normal machining process,

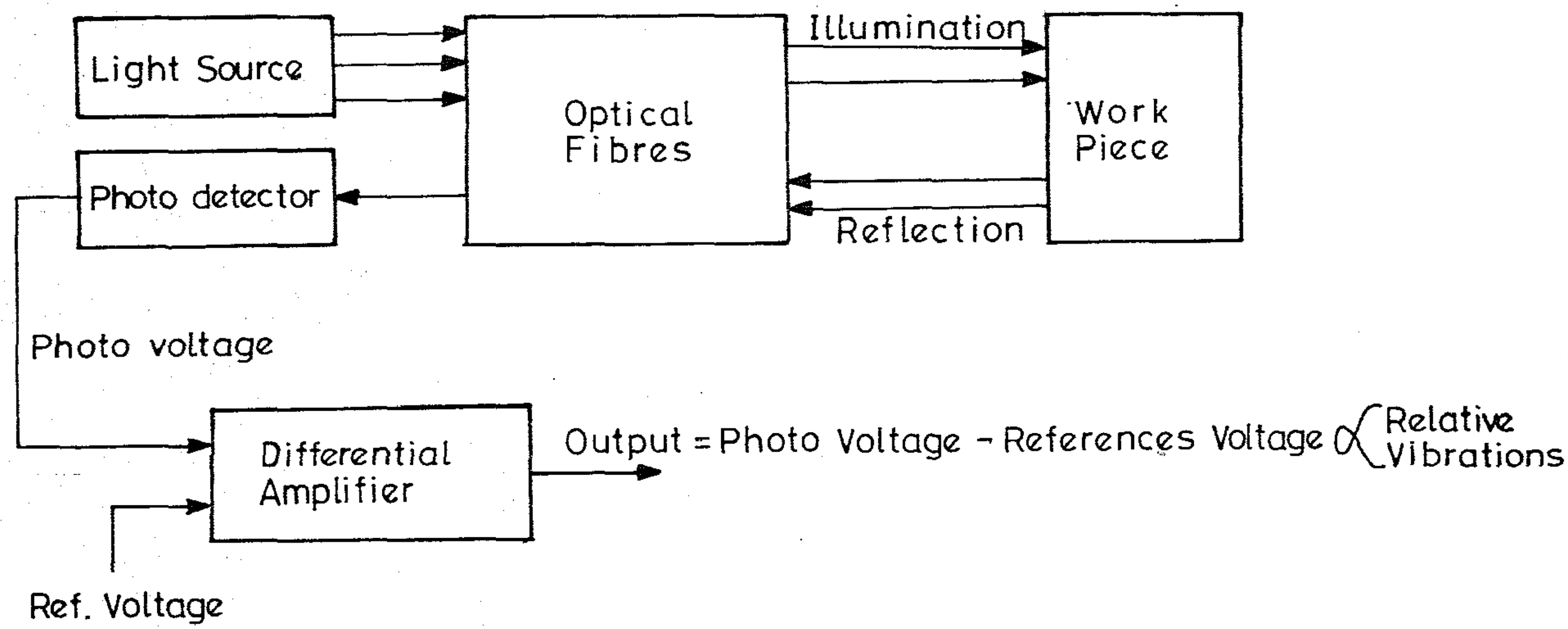


FIG.1·5 Block diagram of the sensing circuit

steady state cutting conditions never exist. Due to nonsteady-state cutting conditions, the forces acting on the tool vary. The variation of these forces causes the vibrations. These vibrations directly affect the dimensional accuracy and surface finish of the workpiece. (Chatter theory has been discussed in Appendix I). These variables forces are functions of feed rate, cutting speed and depth of cut. Since the dimensional inaccuracies are a direct consequence of the changes in the depth of cut due to Chatter, it can be reduced by introducing a similar vibration but with an opposite phase. This in effect, will apply a resistive force to Chatter at the onset of Chatter vibrations. This resistive force can be created by a vibrating tool holder relative to the workpiece. This tool holder (called tool actuator from here onwards) should have the following characteristics.

(a) It should be sufficiently rigid not to allow any unnecessary vibrations. But at the same time should be elastic enough to accommodate the vibrations of the exciter.

(b) The sensing device or probe has to be rigidly held along with the tool.

In addition, the tool actuator must be compact.

The exciting force may be obtained from mechanical, electrodynamic, electrohydraulic, electromagnetic and piezoelectric exciters. The choice of an exciter depends

upon the frequency range and amplitude of the exciting force required for a particular application. Mechanical exciters are seldom used as they have a very low frequency range . Electrohydraulic exciters are particularly suitable for heavy machine tools as they are capable of developing considerable force upto a frequency of 100 Hz. Piezoelectric exciters cannot develop an exciting force of sufficient magnitude at low frequencies. For most machine tool structures the required frequency range is between 10-1000 Hz. This range can be best realized with electrodynamic and electromagnetic exciters.

In conventional NC machines the tool is positioned by positioning motors(13). An electrohydraulic actuator is used(15,16) for this purpose. This actuator has some limitations as discussed in the previous section. An electromagnetic vibrator has been used successfully with frequency range of 40 to 400 Hz and amplitude upto 150 μ m(17). Eventhough the vibrator cum tool holder based on this principle has been used for studying the effects of vibration on the tool life, a feedback loop is designed to control the errors in the vibration. Based on these results(17) an electromagnetic vibrator was selected for the purpose of tool actuation. This electromagnetic vibrator has a frequency limit of 500 Hz.

An ideal in-process measurement and control system will continuously measure and correct all the dimensions of a workpiece as it is being machined. The

accuracy of in-process measurement depends on the output signal to noise ratio. Noise can also be removed by using suitable filters. In any in-process measuring system some amount of noise is unavoidable. This noise will determine the accuracy of the measuring system. The in-process control depends on the resolution of the actuating device and the feedback signal. The feedback signal should have a negative gain or in other words 180° out of phase with the disturbance or error. A schematic arrangement of the control system is shown in Fig. 1.6.

This control system is designed with the assumption that there will be one dominating mode of vibration. That mode of vibration having the maximum amplitude is considered to be the dominating mode.

In this feedback system, the vibration signals, which have a negative gain after the amplification are fedback to the cutting zone through the tool actuator. Any changes in the depth of cut or relative displacement between the tool and the workpiece is being sensed by the sensor. As the depth of cut has the maximum effect on the vibrations and hence surface roughness, a constant depth of cut is to be maintained by the control system . This effectively should improve the surface finish which is the main objective of the present work.

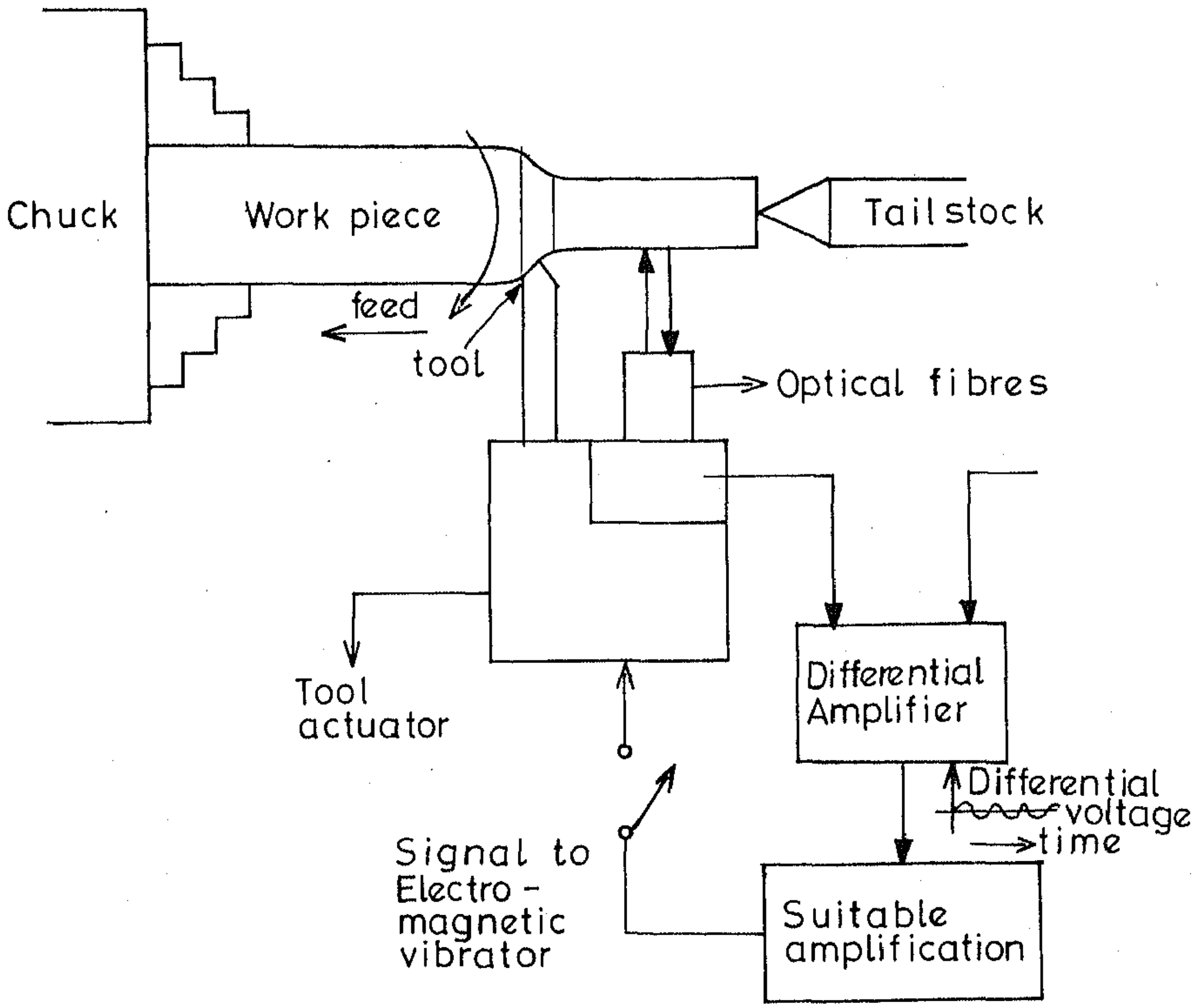


FIG. 1·6 Schematic arrangement of the Control System

Chapter 2

Design and Calibration of the Control System Devices

2.1 Design of the Sensor

As it has been discussed in section 1.3 a photoelectronic displacement sensor has been used in this present work for measuring relative vibrations between the tool and the workpiece.

The sensor consists of a light source, a photodetector and a bifurcated bunch of optical fibres as a probe. As discussed earlier, a high wattage bulb may cause thermal deformation of the set up. Therefore a 5 watt bulb is selected as a light source to illuminate the workpiece surface. In order to keep the light intensity from the source constant, a three pin regulator which provides stiff voltage of 12 volts was used. Also the bulb is held rigidly to one of the optical fibre bundles by a collet. Hence if the light intensity at the receiving fibre varies it is only due to the variation of the distance between the probe and the workpiece surface. The arrangement is shown in Figs. 2.1a and 2.1b.

As the distance between the probe and the workpiece surface varies the power intensity at the receiving fibres also varies.

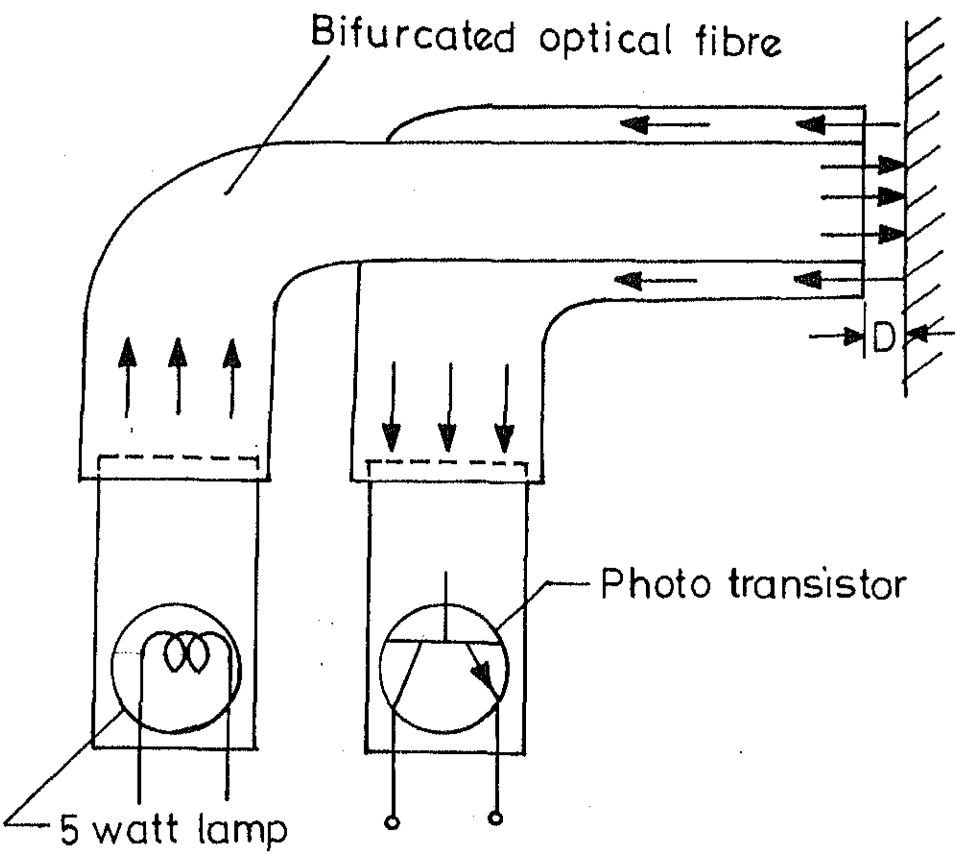


FIG. 2·1a Schematic diagram of a bifurcated optical transducer

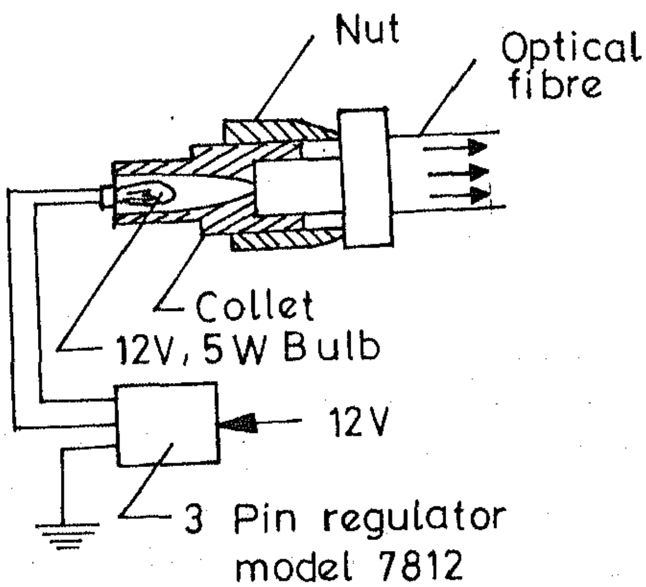


FIG. 2·1b Schematic diagram of the bulb-transducer interface

Photo diode, photo transistor or other photo devices are used for this purpose. A photo diode is more sensitive to optical signals and it can measure signals of very high frequencies. But the output of the photo-diode is usually very low. A phototransistor is less sensitive to optical signals, but has the advantage of amplifying the output signals. Frequencies upto approximately 4 or 5 KHz can be easily measured by a photo transistor. In machine tool operation the first few modes of vibration are the ones which cause Chatter [18]. The frequency range of these modes normally do not cross 1 KHz. Also the amplitude of vibration will be very less, so the change in the power intensity at the receiving fibres will be proportionately less. Considering all these factors a phototransistor is selected for the purpose of converting the optical signals to electrical signals. The nature of variation of the power intensity with the change of distance between the probe and the workpiece surface is shown in Fig. 2.2. The intensity of light increases as the distance between the probe and the workpiece surface increases, the intensity of light reaches a maximum at a certain distance and thereafter it decreases with the increase in the gap.

The converted electrical signal was further amplified by a high gain operational amplifier. However, it is very difficult to detect the small displacement signal with this system, because the power change in the light transmitted is very small. Therefore for better and accurate

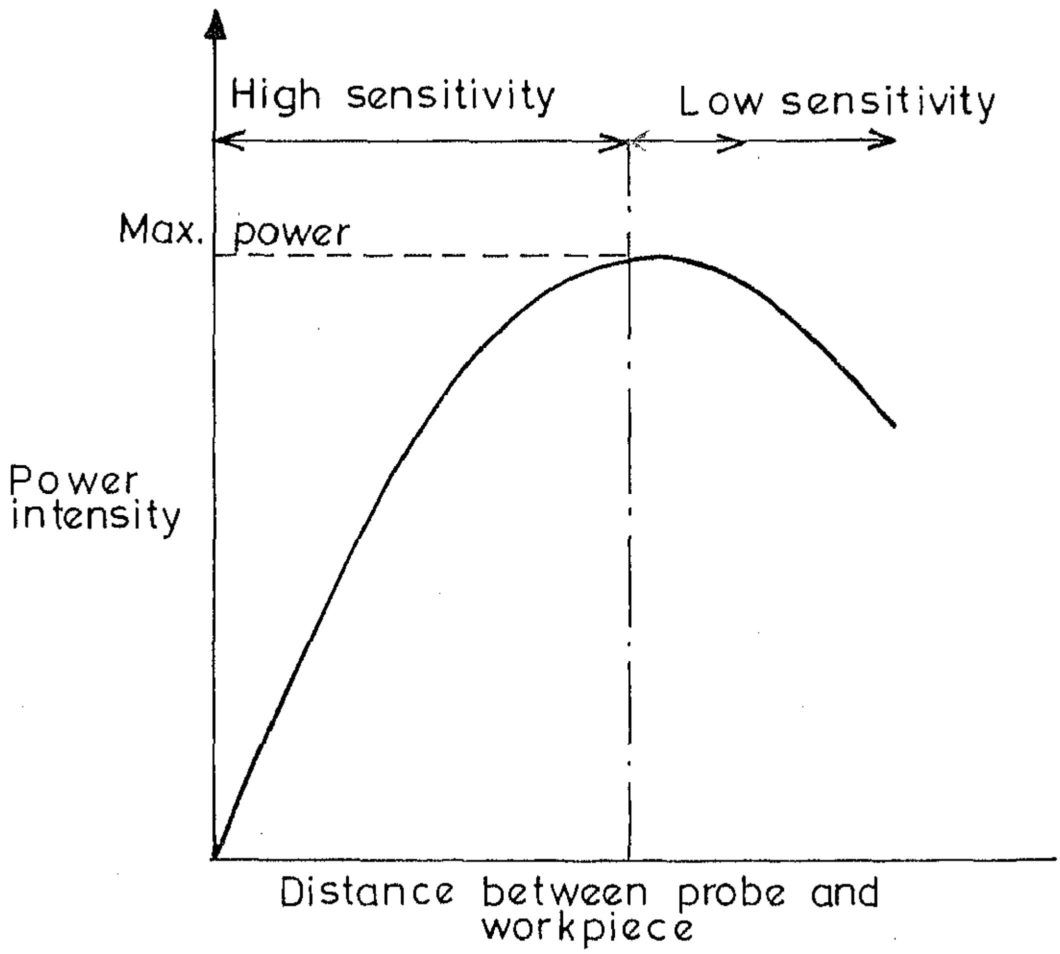


FIG. 2·2 Nature of variation of power intensity with relative distance

measurement of this weak signal a DC voltage (reference voltage) of around 4 volts is introduced, with which the actual signal is differentiated. The reference voltage was supplied through a variable multiturn potentiometer. With this set-up the initial voltage level can be set to within ± 1 millivolt. The variation from this level will be proportional to the change in relative displacement between the probe and the workpiece surface. The sensing circuit is shown in Fig. 2.3.

As the amplification of the signal is high and the operational amplifier is being used as a differential amplifier, the signal-to-noise ratio increases. In order to filter high frequency noises a capacitor of capacitance 2200 pieco farads is connected across the input and output, which is optional. This will limit the measurable frequency to 603 Hz. High frequency noises are eliminated with this R-C filter. The signal is inverted in the first amplifier and then further amplified. The inversion of the signal is for feeding back the signal.

The phototransistor is to be held rigidly at a constant distance from the probe face so that any detectable change in the output from the sensing circuit can be related to the change in the relative displacement only. This is again done by holding the probe with respect to the phototransistor by a collet and nut, which prevent any relative motion between them.

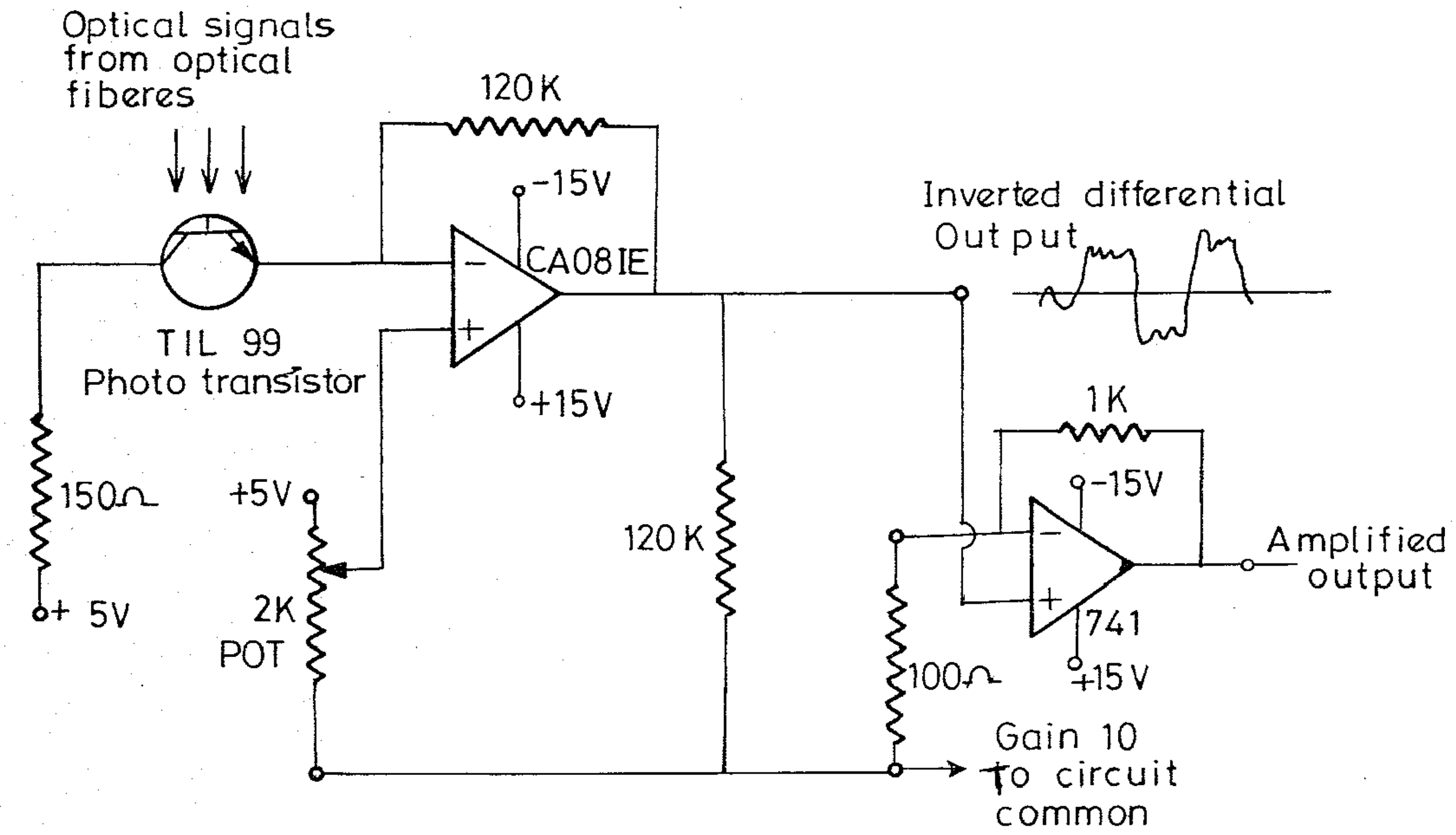


FIG.2·3 SENSING CIRCUIT

2.2 Design of the Tool Actuator

It has been stated in section 1.3 that a tool actuator which is rigid enough to resist machining forces but at the same time respond to exciting force of the vibrator is to be designed. An electromagnetic exciter is designed for the frequency range upto 500 Hz and amplitude range upto 100 m.

2.2.1 Principle of Excitation

When an electromagnet of variable polarity is placed in line with a permanent magnet or an electromagnet of constant polarity, with either of the two being fixed the other magnet will start vibrating at the frequency of magnetic flux variation due to alternate attraction and repulsion. The variable polarity of the electromagnet being created by passing alternating current. The magnetic flux varies with the gap between the magnet and the mass being attracted. Therefore, the force of attraction and repulsion will be different with the change of this gap. This can be done by placing two magnets at the opposite poles of the electromagnet. This arrangement will also double the exciting force. The arrangement is shown in Fig. 2.4.

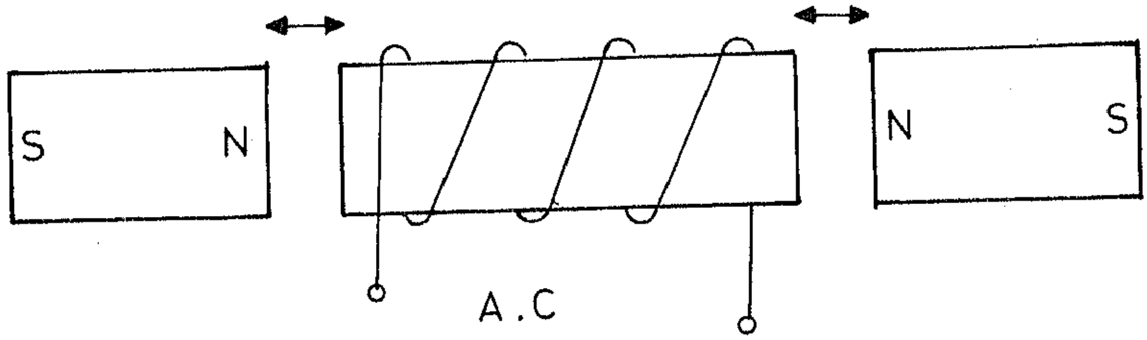


FIG. 2·4 Principle of Excitation

The amount of force generated will be proportional to the current flowing in the coils. The more the current flowing in the coils the more will be the exciting force. The force between two magnetic poles is governed by Coulomb's law

$$F = K \frac{mm'}{d^2} \tag{2.1}$$

where F is the force in newtons, m and m' are the strengths of the poles in ampere meters, d is the distance between the poles in metres and K the proportionality constant and is 10^{-7} webre/amp.mt.

With the arrangement shown in Fig. 2.4 the effective force will be approximately double that given by equation 2.1. As indicated by Eq. 2.1 the force will be more if gap between the magnetic poles is kept at a minimum.

Two electromagnets are held rigidly on a moving mass. Sixteen powerful Alnico permanent magnets, held rigidly, are used for the purpose of attracting and repelling the electromagnets. The cores of electromagnets are assemblies of special silicon steel laminations which are insulated by varnish coating and rectangular in cross-section.

Four permanent magnets having same polarity were clamped to fixed supports on opposite sides of electro-magnets. Provision is made to allow for changing the position of the permanent magnets with respect to the

electromagnets. This arrangement will ensure proper gap setting between the permanent magnets and the electromagnets.

All clamping devices are made of Aluminium and bolted by brass bolts.

Barring secondary effects of distortions it can be assumed that the vibrations produced are in the same phase as the supply voltage which can be assumed to be sinusoidal in nature.

2.2.2 Tool Holder

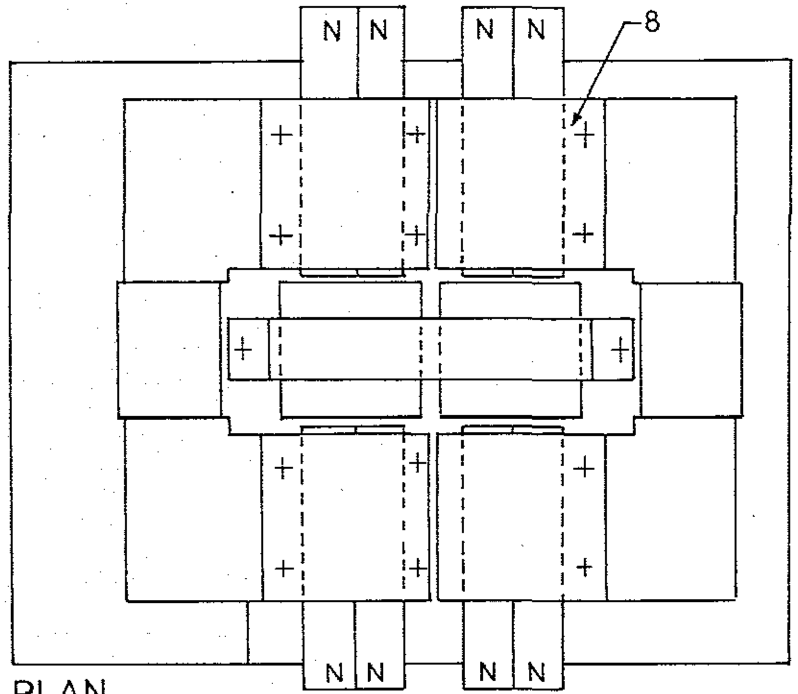
The tool holder has to satisfy some requirements. It should be able to withstand all the forces acting on the cutting tool. A provision has to be made for the excitation force to be transmitted to the tool. The tool holder has to accommodate the sensor probe also. For sensing the vibrations in the radial direction only, the sensor should be placed in the same plane as the tool and also as near to the cutting zone as possible.

As the reflecting surface is cylindrical, to obtain maximum reflection the illumination should be aimed in the radial direction only. It is found from literature review that 0^{o} is the best angle for detecting maximum reflection. At this angle the losses are estimated to be around 30%.

The possible alternatives for positioning the sensor probe are either above the tool directed at an angle to the workpiece surface near the cutting zone or beside the tool. With the first alternative the percentage of losses will increase with increase in angle of incident light. Also stray chips will effect the intensity of reflected light. Holding the sensor probe at a certain angle may also create machining problems.

By holding the sensor probe beside the tool, alignment problems can be eliminated. However, there will be a lag in sensing the vibrations. A reasonable assumption would be that the amplitude of the tool vibrations will be more than workpiece vibrations under good workpiece clamping conditions. Since the probe is located a bit away from the cutting zone along the work-piece axis, it does not actually sense the vibration in the cutting zone but with a transportation lag. Since this transportation lag in most of the similar cases is not more than 0.1 sec. it can be neglected.

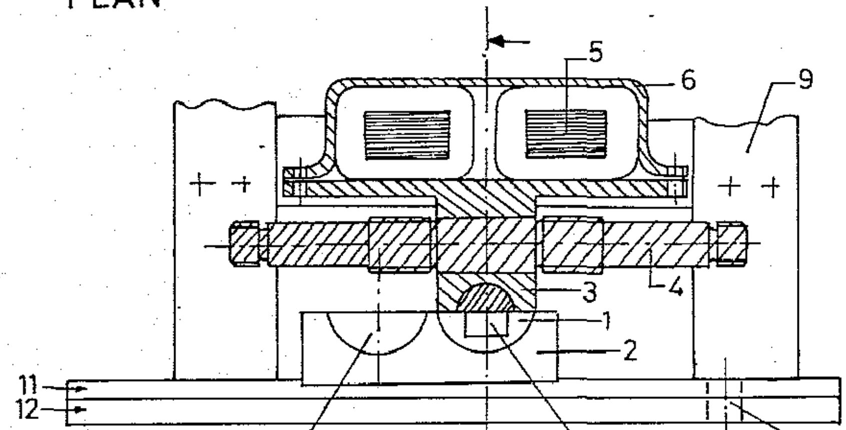
The diameter of the probe which is 28 mms does not permit the probe to be placed nearer than 50 mms from the tool tip. The tool holding block was supported from two either sides and directly from behind the tool. The front end of the tool was freely supported on the base plate to allow excitations of the electromagnetic



PLAN

No	Name	Material	nos
1	Tool Holder	Brass	1
2	Tool & Probe Clamp	Aluminium	1
3	Tool Exciter	"	1
4	Supporting Beam	Brass	1
5	Electro Magnets	Silicon steel	2
6	Electro Magnet Clamp	Aluminium	1
7	Permanent Magnets	Alnico	16
8	Permanent Magnet Clamps	Aluminium	8
9	Side Supports	Cast iron	2
10	Back Support	Cast iron	1
11	Base Plate	Aluminium	1
12	Base Support	Mild steel	1

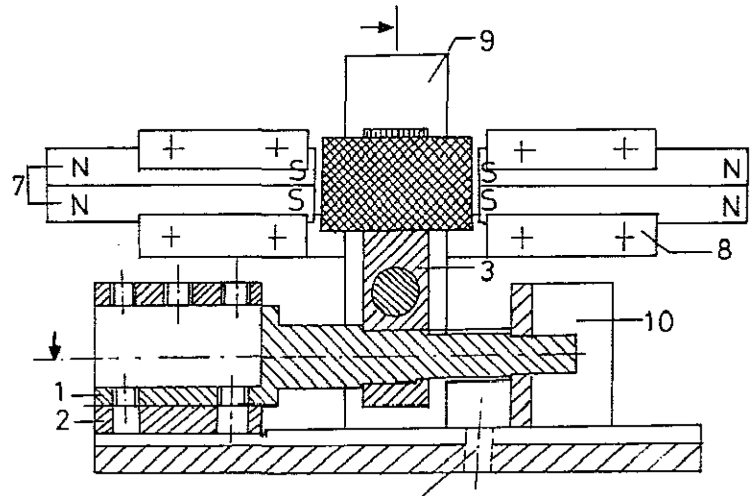
PARTS LIST



Space for Probe

Space for tool

HALF SECTIONAL FRONT VIEW



Holes for clamping on compound slide of tool post

SECTIONAL END VIEW

FIG. 2·5 Name of the drawing Tool Actuator
SCALE- 1·2

vibrator. The detailed drawing is shown in Fig. 2.5.

2.3 Calibration of the Sensor

The calibration of the sensor is necessary to determine the sensitivity and the resolution of the sensor. Sensitivity is defined by the electrical output from the sensor in mV to the mechanical input in μ m. The resolution is given by the minimum change in mechanical input to record a change in the electrical output of the sensor.

Both static and dynamic calibrations of the sensor are necessary. Static calibration is necessary to determine the optimum initial distance between the probe and the work-piece surface. The distance is termed as optimum when the output from the sensing circuit shows more linearity and maximum sensitivity. In the present case a distance less than 2 mm may not be possible; because of the fact that the chips in the cutting zone may come into contact with the probe surface and damage it.

Various factors affect the sensitivity of the sensor. The main factors affecting the performance of the sensor can be listed as follows:

(i) Workpiece diameter: A change in workpiece diameter may change the intensity of the reflected light, i.e. the

signal of relative vibration between the tool and the workpiece, since along with the change in workpiece diameter a new surface is exposed which may differ from the previous surface in surface finish.

(ii) Workpiece material: The reflectivity of workpiece surfaces vary for different materials. Hence the sensitivity varies.

(iii) Surface finish: The reflectivity of surfaces change with surface finish. The better the surface finish more will be the sensitivity.

(iv) Uncontrolled factors: Various other factors like stray chips; circularity of the workpiece etc. will effect the sensitivity of the sensor.

The sensor was calibrated when machining mild steel workpieces; with varying cutting conditions. The cutting conditions are given in table 2.1. The workpiece was machined both with and without tailstock centre; the sensor was calibrated for both the cases. The variation of electrical output to the variation of the relative distance between the probe and the workpiece has been plotted in Fig. 2.6. The results are tabulated in Table 2.2.

Table 2.1 : Cutting conditions for Static Calibration

Cutting Conditions:
Workpiece material: Mild steel
Tool: High speed steel
Workpiece chucked at one end
(a) Without revolving centre
(b) With revolving centre

Sl. No.	Workpiece diameter mms.	Cutting speed m/min	Speed RPM	Feed mm/rev.	Depth of cut mm.	Surface roughness μ m (a)	Surface roughness μ m (b)
1.	38.52	24.20	200	0.05	0.3	21	20.1
2.	38.52	24.20	200	0.075	0.3	16	12.0
3.	38.52	24.20	200	0.1	0.3	15.5	11.5
4.	38.52	30.25	250	0.05	0.3	13	18.0
5.	38.52	30.25	250	0.075	0.3	20.5	18.5
6.	38.52	30.25	250	0.1	0.3	15	19.0
7.	38.52	38.72	320	0.05	0.3	12	13.0
8.	38.52	38.72	320	0.075	0.3	19	20
9.	38.52	38.72	320	0.1	0.3	17	19.8

Table 2.2 : Static Calibration Results
(a) Without tailstock centre

Sl. No.	C.C.1		C.C.2		C.C.3		C.C.4		C.C.5		C.C.6	
	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)
1	0	0	0	0	0	0	0	0	0	0	0	0
2	110	50	80	10	210	91	200	10	90	43	120	10
3	210	70	350	70	260	133	300	40	110	67	190	70
4	330	160	435	100	325	192	410	60	190	118	300	183
5	400	200	500	140	380	234	500	169	276	177	400	301
6	550	310	590	210	500	329	600	260	300	191	710	649
7	680	390	660	252	600	402	700	350	390	249	800	729
8	800	480	700	280	700	506	800	450	460	290	1000	965
9	1000	650	810	360	810	597	900	550	550	353	1110	1123
10	1200	810	900	420	900	678	1000	652	610	391	1200	1220
11	1400	990	1000	501	1000	763	1110	765	830	545	1420	1513
12	1590	1183	1120	593	1115	893	1290	954	930	610	1500	1647
13	1810	1435	1210	672	1220	985	1395	1087	1010	670	1600	1780
14	1910	1557	1300	749	1310	1980	1500	2106	1210	833	1800	2100
15	2000	1682	1400	857	1400	1184	1600	1331	1400	993	2000	2450
16	2200	1911	1520	943	1600	1427	1700	1459	1500	1089	2150	2850
17	2400	2170	1610	1031	1700	1553	1810	1601	1700	1270	2250	3000
18	2500	2300	1810	1233	1800	1691	1910	1747	1900	1469	2350	3080
19	2600	2430	2000	1467	1900	1821	1990	1876	2010	1589	2510	3380
20	2650	2490	2100	1575	2000	1960	2070	1990	2200	1781	2700	3740
21	2700	2540	2220	1721	2100	2122	2110	2060	2310	1927	2800	3960
22	2780	2600	2300	1810	2210	2250	2210	2240	2410	2070	3000	4340
23	2900	2780	2400	1965	2300	2379	2400	2500	2550	2110	3110	4560
24	3010	2930	2500	2060	2400	2520	2700	3040	2600	2220	3200	4700
25	3110	3050	2600	2180	2500	2660	2810	3230	2700	2340	3400	4070

Continued....

Table 2.2 (Continued) :

Sl. No.	C.C.1		C.C.2		C.C.3		C.C.4		C.C.5		C.C.6	
	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)
26	3220	3180	2800	2450	2600	2820	2900	3380	2820	2480	3500	5280
27	3290	3260	2900	2580	2700	2980	3110	3750	2900	2570	3600	5430
28	3360	3350	3000	2710	2800	3130	3200	3930	3000	2680	3830	5810
29	3455	3450	31000	2840	2900	3280	3300	4090	3100	2790	3900	5920
30	3505	3510	3300	3090	3010	3440	3500	4430	3200	2900	4000	6080
31	3600	3610	3500	3340	3200	3720	3600	4610	3310	3030	4200	6450
32	4010	4050	3600	3450	3410	4020	3810	4780	3500	3190	4410	6650
33	4500	4440	3700	3570	3510	4170	4000	5220	3600	3300	4640	6930
34	5000	4750	3990	3890	3600	4290	4210	5640	3700	3380	4750	7050
35	5490	4940	4210	4110	3700	4910	4310	5740	3910	3570	4920	7230
36	6000	5030	4400	4360	3920	4700	4420	5810	4000	3640	5000	7290
37	6450	5040	4610	4460	4000	4740	4800	6030	4200	3800	5120	7450
38	6600	5030	4730	4550	4245	5060	4810	6260	4400	3990	5300	7520
39	6700	5030	5010	4740	5390	5210	5000	6440	4550	4020	5410	7580
40	6800	4980	5120	4800	4660	5400	5120	6540	4700	4120	5500	7620
41	6900	4940	5310	4900	4810	5640	5250	6660	4900	4210	5600	7670
42	7000	4880	5500	5000	6000	5760	5440	6760	5010	4260	5700	7710
43	–	–	6000	5120	6210	5860	5610	6860	5210	4340	5920	7770
44	–	–	6210	5150	6430	5940	5810	6960	5440	4410	6100	7820
45	–	–	6300	5160	6800	6080	5990	7010	5625	4440	6200	7840
46	–	–	6570	5170	7020	6130	6020	7070	5750	4460	6460	7820
47	–	–	6700	5160	7050	6150	6390	7080	6000	4480	6610	7810
48	–	–	7010	5130	7100	6150	6500	7080	6200	4480	6830	7770
49	–	–	7300	5080	7290	6170	6700	7080	6700	4480	7000	7730
50	–	–	7410	5010	7500	6170	7000	7020	6800	4470	7400	7540
51	–	–	7570	4960	8010	6100	7200	6860	7000	4420	–	–
52	–	–	7710	4870	8500	5880	–	–	7300	4350	–	–
53	–	–	8000	4680	–	–	–	–	–	–	–	–

Continued.....

Table 2.2 (Continued):

Sl. No.	C.C.7		C.C.8		C.C.9	
	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)
1	0	0	0	0	0	0
2	100	10	120	12	130	60
3	200	22	240	73	220	131
4	280	87	350	175	400	308
5	420	253	400	212	500	393
6	500	351	500	311	600	487
7	640	520	600	407	800	665
8	710	603	730	535	920	776
9	890	824	850	648	1000	855
10	1000	965	1000	794	1100	973
11	1100	1087	1210	1015	1320	1195
12	1300	1380	1400	1231	1500	1420
13	1400	1555	1540	1417	1690	1615
14	1610	1881	1770	1750	1900	1970
15	1820	2270	1870	1920	2010	2130
16	2010	2640	2000	2110	2110	2310
17	2200	3010	2200	2250	2150	2450
18	2300	3210	2300	2610	2310	2580
19	2400	3470	2410	2750	2400	2730
20	2480	3600	2510	2920	2500	2900
21	2600	3860	2700	3090	2690	3210
22	2710	4100	2800	3400	2810	3410
23	2810	4330	2900	3620	3000	3690
24	2900	4520	3000	3780	3200	4010
25	3000	4750	3100	3960	3310	4180
26	3100	4960	3290	4280	3420	4350
27	3200	5180	3500	4600	3600	4600
28	3300	5390	3600	4780	3810	4750
29	3420	5660	3710	4940	3910	5020
30	3650	6110	3810	5080	4000	5120
31	3900	6580	4000	5350	4130	5360
32	4000	6740	4150	5520	4220	5430
33	4100	6920	4320	5780	4420	5670

Continued...

Table 2.2 (Continued):

Sl. No.	C.C.7		C.C.8		C.C.9	
	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)
34	4200	7090	4520	5930	4550	5700
35	4400	7490	4680	6080	4700	5820
36	4530	7560	4820	6210	4830	5920
37	4610	7650	4920	6260	5000	6030
38	4810	7800	5120	6400	5180	6160
39	5000	8070	5250	6500	5300	6220
40	5200	8240	5460	6570	5410	6250
41	5350	8380	5600	6630	5500	6280
42	5570	8460	5730	6670	5670	6340
43	5650	8500	5900	6700	5810	6370
44	5860	8560	6000	6720	6000	6390
45	5930	8590	6220	6720	6100	6400
46	6040	8610	6310	6680	6370	6410
47	6300	8640	6600	6630	6700	6370
48	6400	8640	6810	6580	6800	6360
49	6610	8620	7000	6580	6820	6360
50	6730	8600	7500	6400	7000	6300
51	6810	8570	–	–	–	–

Continued....

Table 2.2 (Continued):

(b) With tailstock centre

Sl. No.	C.C.1		C.C.2		C.C.3		C.C.4		C.C.5		C.C.6	
	D (µms)	O (mV)	D (µms)	O (mV)	D (µms)	O (mV)	D (µms)	O (mV)	D (µms)	O (mV)	D (µms)	O (mV)
1	0	0	0	0	0	0	0	0	0	0	0	0
2	50	13	50	31	80	53	100	75	100	53	100	42
3	120	45	100	68	120	99	200	125	150	92	250	81
4	320	163	400	363	210	187	400	294	200	134	400	174
5	500	323	550	440	410	373	500	363	310	185	500	243
6	750	501	700	701	500	459	610	471	410	241	800	423
7	1000	647	800	879	690	635	700	562	520	362	1000	567
8	1120	723	920	1038	800	750	800	638	680	541	1190	728
9	1230	762	1000	1157	900	885	910	750	800	649	1310	813
10	1300	873	1100	1319	1000	1006	1000	823	1000	825	1400	915
11	1450	1000	1310	1657	1200	1372	1150	976	1190	1045	1550	1065
12	1750	1200	1450	1875	1350	1611	1280	1146	1300	1153	1700	1256
13	2000	1400	1600	2150	1500	1830	1400	1238	1430	1265	1810	1388
14	2100	1474	1800	2540	1650	2090	1500	1349	1510	1327	1900	1438
15	2210	1555	1900	2740	1800	2360	1700	1588	1600	1408	2000	1696
16	2370	1674	2000	2940	1930	2640	1800	1711	1700	1493	2120	1840
17	2500	1770	2100	3150	2010	2840	1900	1840	1800	1579	2200	2040
18	2650	1881	2200	3350	2100	3050	2000	1973	1900	1668	2300	2180
19	2750	1955	2350	3650	2200	3280	2100	2120	2010	1757	2400	2330
20	2900	2070	2510	3970	2300	3490	2200	2270	2100	1895	2500	2480
21	3000	2250	2750	4450	2400	3710	2300	2430	2230	2090	2650	2700
22	3100	2340	2900	4760	2500	3920	2400	2580	2360	2290	2700	2770
23	3200	2450	3000	4970	2650	4250	2500	2730	2500	2510	2850	3000
24	3400	2620	3100	5110	2770	4510	2700	2880	2620	2690	3000	3220
25	3600	2770	3250	5430	2850	4680	2900	3030	2730	2860	3100	3370
26	3750	2900	3500	5850	2900	4790	3000	3180	2800	2970	3230	3570
27	4000	3100	3800	6460	3000	5010	3100	3340	2910	3140	3390	3700
28	4100	3190	4000	6800	3100	5235	3250	3650	3000	3290	3550	4060
29	4250	3310	4250	7110	3200	5460	3400	3870	3250	3630	3700	4180
30	4500	3540	4500	7490	3310	5690	3500	3990	3500	3890	3820	4260

Continued....

Table 2.2 (Continued):

Sl. No.	C.C.1		C.C.2		C.C.3		C.C.4		C.C.5		C.C.5	
	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)	D (μms)	O (mV)
31	4700	3740	4700	7730	3430	5940	3630	4120	3700	4100	4000	4400
32	5000	3970	5000	7950	3650	6430	3800	4360	4000	4480	4100	4510
33	5250	4200	5250	8100	3750	6650	4000	4550	4090	4580	4250	4600
34	5500	4410	5500	8200	3900	6960	4150	4700	4240	4690	4500	4780
35	5750	4630	5800	8250	4000	7160	4400	4990	4380	4820	4750	4950
36	6000	4710	6000	8260	4250	7640	4550	5020	4620	4980	5000	5100
37	6200	4750	6500	8260	4500	8040	4700	5750	4850	5150	5550	5300
38	6500	4780	7000	8000	4600	8140	5000	5390	5000	5230	5700	5380
39	6700	4780	7500	7780	4750	8260	5200	5410	5240	5310	6000	5400
40	7000	4600	–	–	4900	8350	5500	5530	5500	5370	6250	5400
41	7250	4480	–	–	5000	8370	5750	5580	5730	5430	6500	5350
42	–	–	–	–	5500	8380	6000	5610	6000	5470	7000	4950
43	–	–	–	–	5750	8390	6500	5610	6500	5470	–	–
44	–	–	–	–	6000	8390	6750	5580	7000	5460	–	–
45	–	–	–	–	6250	8370	7000	5520	7500	5340	–	–
46	–	–	–	–	7000	8120	–	–	8000	5010	–	–

Continued...

Table 2.2 (Continued):

Sl. No.	C.C.7 D (μms)	C.C.7 O (mV)	C.C.8 D (μms)	C.C.8 O (mV)	C.C.9 D (μms)	C.C.9 O (mV)
1	0	0	0	0	0	0
2	100	38	100	46	100	57
3	200	59	200	121	210	135
4	310	120	300	180	300	198
5	400	230	410	255	400	270
6	520	413	500	315	500	350
7	630	679	600	378	590	421
8	700	765	900	593	700	499
9	800	885	1000	664	810	589
10	900	1010	1150	780	900	658
11	1000	1152	1300	898	1000	738
12	1100	1312	1500	1050	1210	909
13	1210	1479	1750	1252	1300	997
14	1330	1648	2000	1489	1420	1100
15	1450	1857	2100	1679	1500	1170
16	1600	2110	2250	1814	1600	1253
17	1710	2290	2400	1949	1750	1390
18	1800	2460	2500	2040	1900	1542
19	1900	2660	2600	2130	2000	1653
20	2000	2850	2750	2760	2100	1761
21	2100	3040	2930	2420	2200	1874
22	2200	3130	3300	2460	2300	1981
23	2300	3320	3100	2500	2410	2090
24	2410	3530	3200	2620	2600	2280
25	2530	3760	3330	2750	2750	2430
26	2700	4000	3500	2970	2800	2480
27	2800	4190	3600	3140	2900	2580
28	2900	4390	3750	3300	3000	2680
29	3000	4600	4000	3520	3100	2780
30	3100	4670	4150	3630	3200	2890

Continued....

Table 2.2 (Continued) :

Sl. No.	C.C.7		C.C.8		C.C.9	
	D (µms)	O (mV)	D (µms)	O (mV)	D (µms)	O (mV)
31	3210	4880	4400	3750	3310	3030
32	3300	5050	4650	3970	3430	3190
33	3410	5220	4900	4120	3600	3490
34	3550	5460	5000	4250	3810	3710
35	3720	5750	5500	4550	4000	3910
36	3900	6050	5700	4700	4250	4020
37	4000	6110	5850	4750	4500	4160
38	4100	6260	5900	4800	4800	4670
39	4200	6410	6000	4840	5000	4800
40	4300	6550	6200	4880	5250	4950
41	4400	6690	6410	4900	5500	5050
42	4710	7090	6600	4910	5700	5100
43	5000	7390	6750	4910	5000	5200
44	5200	7600	7000	4900	6500	5200
45	5450	7770	7100	4880	7000	5150
46	5600	7860	–	–	7250	5070
47	5800	7990	–	–	–	–
48	6010	8040	–	–	–	–
49	6300	8050	–	–	–	–
50	7000	7800	–	–	–	–

D = Distance between the probe and the workpiece.

O = Output voltage from the sensing circuit.

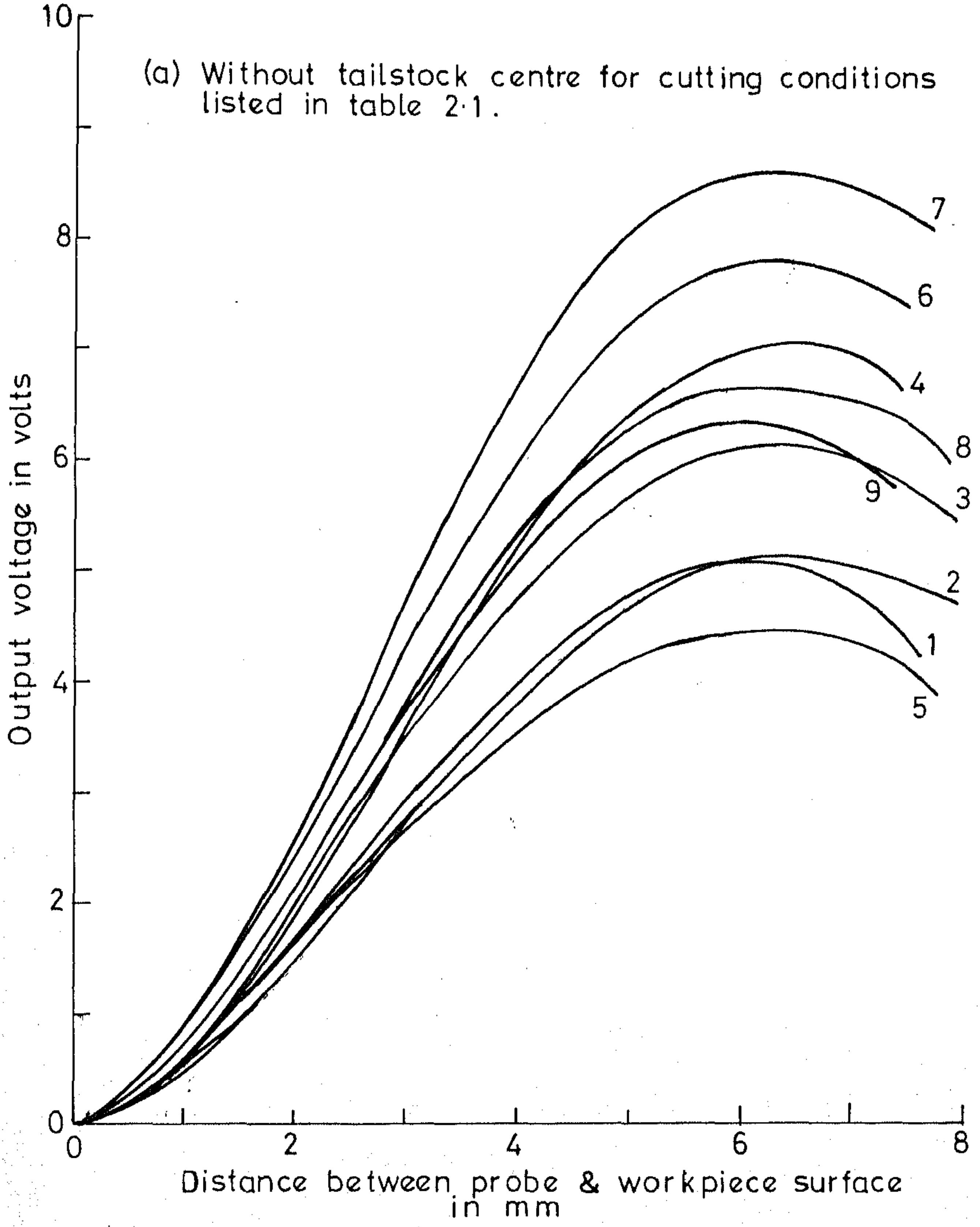


FIG. 2·6 Variation of output voltage with distance

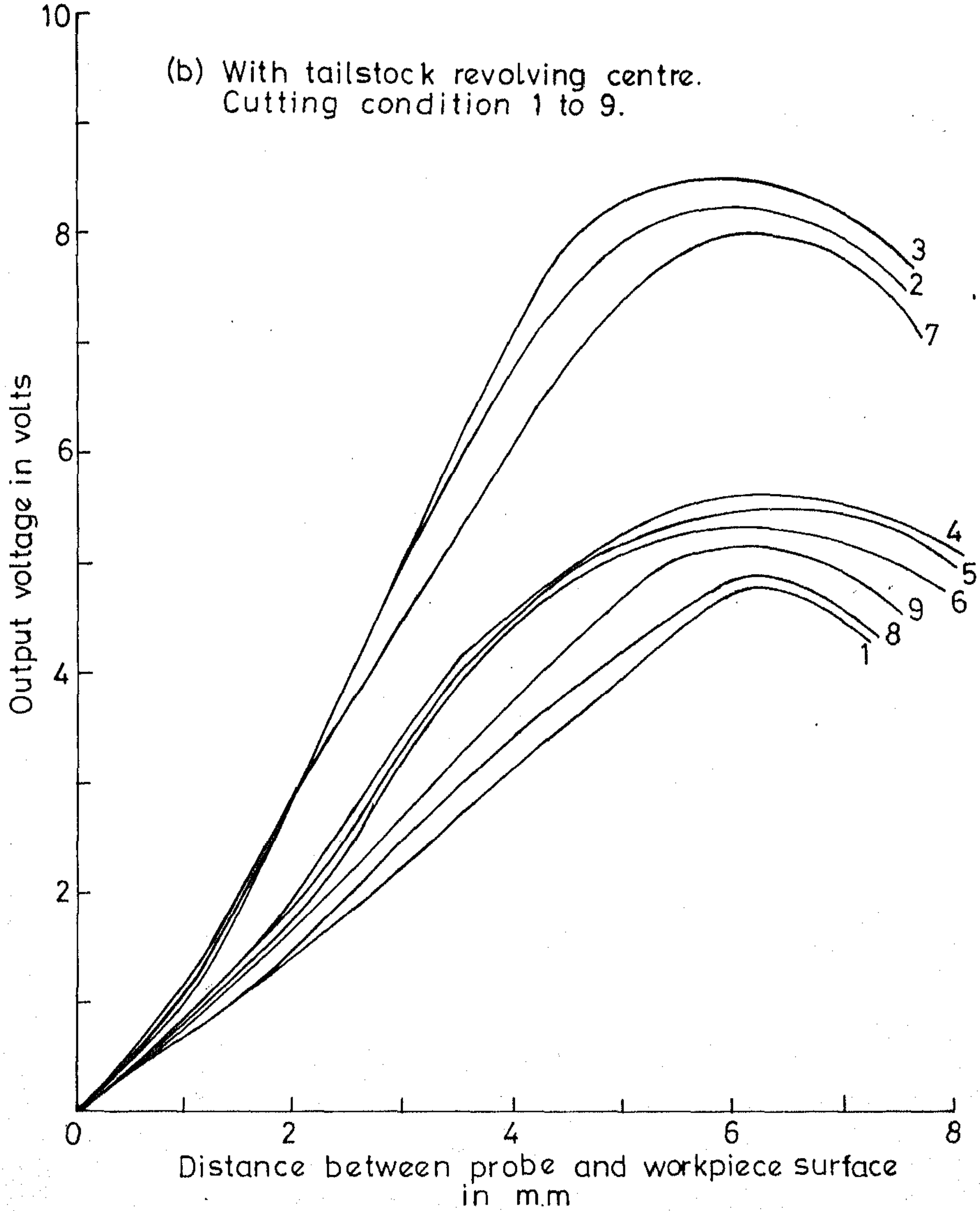


FIG. 2·6 Variation of output voltage with distance

For initial setting, the probe was brought into contact with the workpiece surface. The output from the operational amplifier was set to zero by the potentiometer. Then the probe attached to the tool post-cum-electro-magnetic vibrator is gradually taken away from the work-piece surface. The gap between the probe and the machined workpiece surface was measured by a dial gauge of least count 0.01 mm. The output was measured by a digital multimeter.

It is evident from the results that the sensor is showing more linearity in the region between 1900 and 3200 μ ms. The linearity in this region can be defined by the equation

$$V = s \cdot x + b \text{ mV} \qquad (2.2)$$

where V is the output from the amplifier in millivolts and x is the distance in μ ms between the probe and the workpiece surface. 's' and 'b' are constants to be determined from calibration curves. 's' is the sensitivity of the sensing circuit in millivolts/μm and 'b' is a constant in millivolts.

The error in linearity in the region was found to be less than 2.5% for all the cutting conditions.

The sensitivity of the sensing circuit for all the cutting conditions is given in Table 2.3.

Table 2.3 : Sensitivities for Various Cutting Conditions

Sl. No.	Cutting condition	Sensitivity 's' mV/μm
1	1	0.765
2	2	2.026
3	3	2.206
4	4	1.157
5	5	1.532
6	6	1.271
7	7	1.682
8	8	1.068
9	9	1.043

Workpiece is machined with tailstock centre.

The calibration curves in Fig. 2.6(b) show a definite trend. With better surface finish the sensitivity of the sensor has improved. But some of the calibration curves in Fig. 2.6(a) overlap one another. This may be due to the fact that the workpiece was machined without a tailstock centre, which will produce ovality in the workpiece. As the curvature of the workpiece surface varies the sensitivity of the sensor varies for surfaces having same surface finish. From static calibration it was determined that the sensitivity of the sensing is s mV/μ m (See Table 2.3). Therefore, for a change of 1 μm in the gap between thepprobe and the workpiece surface the change in output of the sensor has to be 's' mV. But under dynamic conditions this conclusion may not hold good. In order to ascertain the sensitivity of the sensing circuit and to determine the resolution of the sensing circuit dynamic calibration was done for one of the cutting conditions.

The dynamic calibration was done using an All-American vibration fatigue testing machine, model 150-VP-T (Vertical) with an adjustable frequency range of 5 to 60 Hz and peak to peak amplitude upto 0.150". The machined workpiece was rigidly clamped to the table of the machine. The sensor probe was held at a distance of 2.65 mms from the workpiece surface. The gap being set by a height gauge. The peak-to-peak amplitude was

measured by a piezoelectric transducer connected to a vibration meter of type 2511. The least count of the vibration meter being 1μm and frequency range 0.3 Hz to 15 KHz.

With an initial gap of 2.65 mm the output from the operational amplifier was set to zero by varying the input from the potentiometer. The output was measured by an digital storage oscilloscope. The calibration set-up is shown in Fig. 2.7. The results are tabulated in Table 2.4 and plotted in Fig. 2.8.

It is evident from the results that upto a peak-to-peak amplitude of 100 μm the dynamic sensitivity of the sensor is approximately same as the static sensitivity of the sensor. The error in the output from the sensor is less than ±2% in the frequency range of 10 to 500 Hz. The results also show that for peak to peak amplitude of vibration of more than 100μm the variation in the sensitivity of the sensor is not much. The only variation is in the higher frequency range. The frequency measured by the sensor did not show any change from that of the vibrating frequency.

For frequencies above 50 Hz, the sensor was calibrated using an electrodynamic vibramate exciter, model PM-25. This calibration was essential to determine the frequency response characteristics of the sensor.

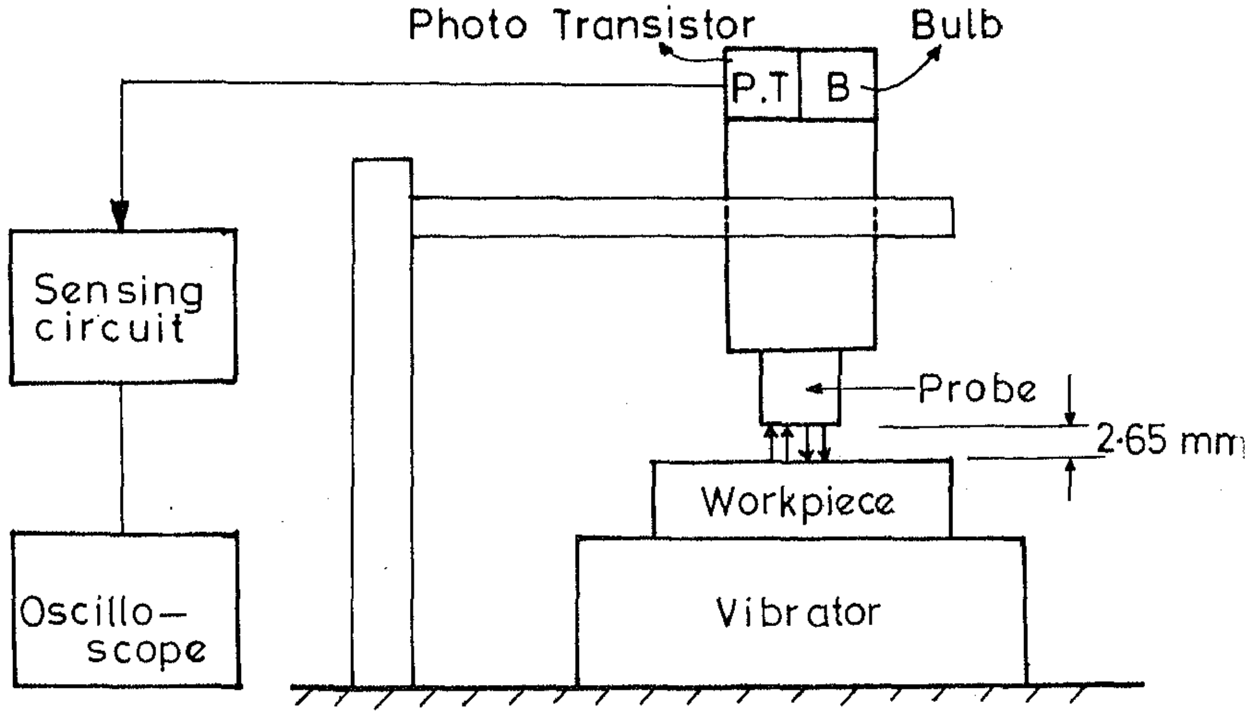


FIG. 2·7 Block diagram of sensor calibration (Dynamic) setup

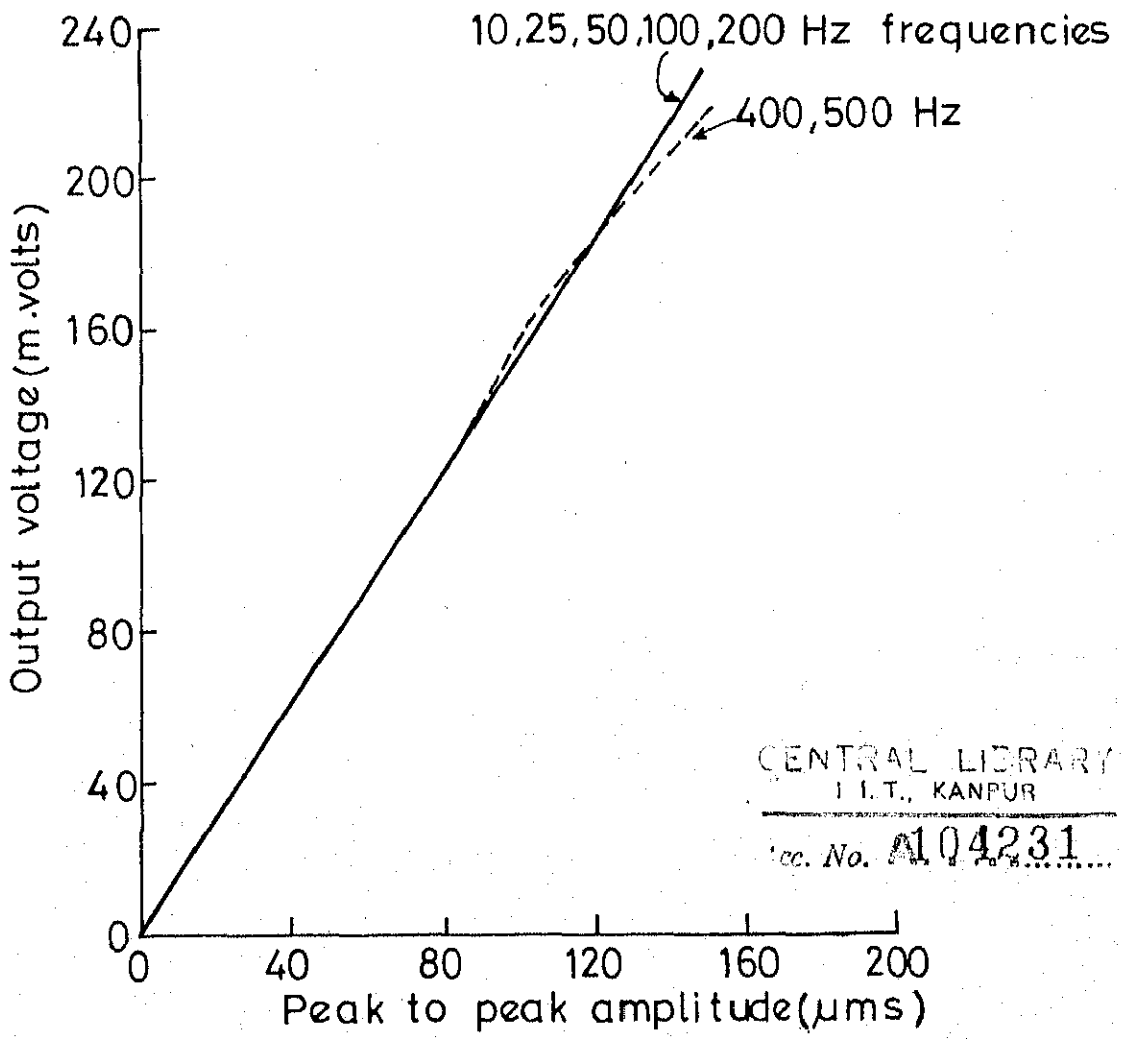


FIG. 2·8 Dynamic calibration curve

Table 2.4 : Dynamic Calibration Results

Workpiece surface roughness: 18.5μm
Diameter: 37.92 mms.
Static sensitivity: 1.532 mV/μm
Cutting speed: 30.25 m/min.
Feed: 0.075 mm/rev.
Dynamic sensitivity: 1.54 mV/μm

Sl.No.	p-p amp. μ ms.	10 Hz p-p vol. (mV)	25 Hz p-p vol. (mV)	50 Hz p-p vol. (mV)	100 Hz p-p vo. (mV)	200 p-p vol. (mV)	300 p-p vol. (mV)	400 p-p vol. (mV)	500 p-p vol. (mV)
1	5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
2	10	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
3	20	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5
4	30	46	46	46	46	46	46	46	46
5	40	62	62	62	62	62	62	62	62
6	50	76	76	76	76	76	76	76	76
7	75	116	116	116	116	116	116	116	116
8	90	140	140	140	140	140	140	140	140
9	100	155	155	155	155	155	155	160	160
10	150	230	230	230	230	230	230	220	220

The resolution of the sensor was found to be 1μm. A change in the output from the sensor was observed for a change in peak-to-peak amplitude of 1μm.

2.4 Calibration of the Tool Actuator

The tool actuator has been shown in Fig. 2.5. The excitation force can be varied both by changing the gap between the electromagnets and the permanent magnets and by varying the current flowing in the coils of electromagnets. The gap between the magnets has to be kept as less as possible to minimize the leakage of flux. This will also increase the excitation force.

The assembled set up (Fig. 2.5) was clamped rigidly to the compound slide. The peak-to-peak amplitude of vibrations was measured by a piezoelectric transducer connected to a vibration meter of type 2511. For initial testing purpose voltage was applied across the coils of the electromagnets through a variac. It is assumed that the variation of magnetic flux is proportional to supply voltage which is again assumed to be sinusoidal in nature. The readings are tabulated in Table 2.5. The error in the amplitude of the vibration was observed to be $\pm$ 2μm because of the variation in the magnetic force with vibration.

The frequency range of the vibrator is determined by passing a signal of through a waveform Generator and a power amplifier. It is observed that at frequencies higher than 400 Hz, the peak-to-peak amplitude showed more variation at higher amplitudes. The performance of the vibrator is steady in the frequency range of 10 to 400 Hz. The results have been tabulated in Table 2.5 and the variation of peak-to-peak amplitude with variation of the voltage and frequency have been plotted in Fig. 2.9.

The results show that for exciting the tool holder to amplitudes more than 80 μm, the required excitation voltage varies more for different frequencies. Since this variation is negligible a mean excitation voltage for unit peak-to-peak amplitude for the frequency range of 25 to 400 Hz can be calculated. The mean excitation voltage for a peak-to-peak amplitude of 1 μm was calculated to be 0.13 volts (R.M.S.).

2.5 Feedback Circuitry and Instrumentation

The signals from the sensing circuit have to be suitably amplified and passed to the coils on the electromagnet in order to compensate for the Chatter. The signal should be 180° out of phase with the relative vibrations of the tool and the workpiece or else it will tend to make the system unstable. Here it has been assumed

Table 2.5 : Response of the Tool Actuator to Frequency and Peak to Peak Amp.

Sl. No.	Frequency Voltage (volts) (RMS)	25 Hz p-p amp. (μms)	50 Hz p-p amp. (μms)	100 Hz p-p amp. (μms)	200 Hz p-p amp. (μms)	400 Hz p-p amp. (μms)
1	3	9	9	9	9	9
2	3.45	11	11	11	11	11
3	4.18	16	16	16	16	16
4	4.88	22	22	22	22	22
5	5.35	28	28	28	28	28
6	6.12	30	30	30	30	30
7	6.59	36	36	36	35	35
8	8.85	58	56	55	54	53
9	9.75	66	66	64	62	62
10	10.00	69	68	65	65	63
11	11.00	82	81	77	74	72
12	11.98	95	92	85	84	80
13	13.00	105	101	94	91	87

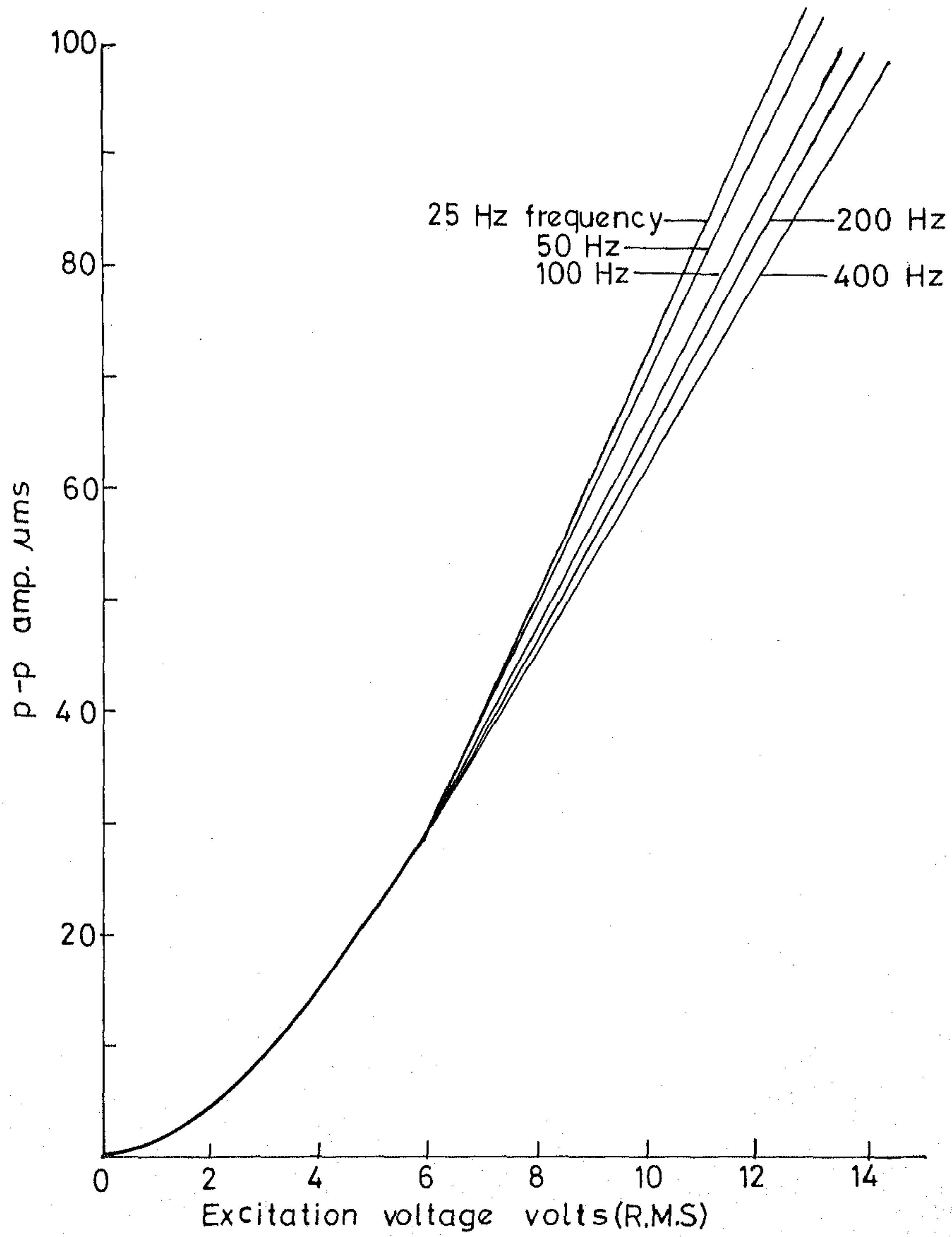


FIG. 2·9 Actuator response to Excitation voltage and frequency.

that only one principal mode of vibration exists which makes the system of machine tool and cutting process unstable. The signal has been preamplified by the first operational amplifier (Fig. 2.3). The voltage level at the output from the operational amplifier will be of the order of millivolts and the current level will be of the order of milliamperes. But the requirements for the exciter is of the order of a few volts and amperes. For a particular cutting condition the surface finish and hence the sensitivity of the sensing circuit will be constant. But for different cutting conditions and hence for different surface finishes the sensitivity varies. Therefore, for same vibration amplitude the output from the sensing circuit differs for different cutting conditions. The device which passes the feedback signal to the exciter should have variable amplification. For this purpose a power amplifier (Appendix III) with variable amplification is selected. Since the input requirements of the power amplifier is more than the signal voltage from the sensing circuit, a third operational amplifier is used. Low frequency noises which are below 25 Hz are bypassed and filtered by the power amplifier. This is desirable during the function of the exciter because, otherwise, low frequency noises may result in relatively high displacement of the exciter. The feedback circuitry is shown in Fig. 2.10.

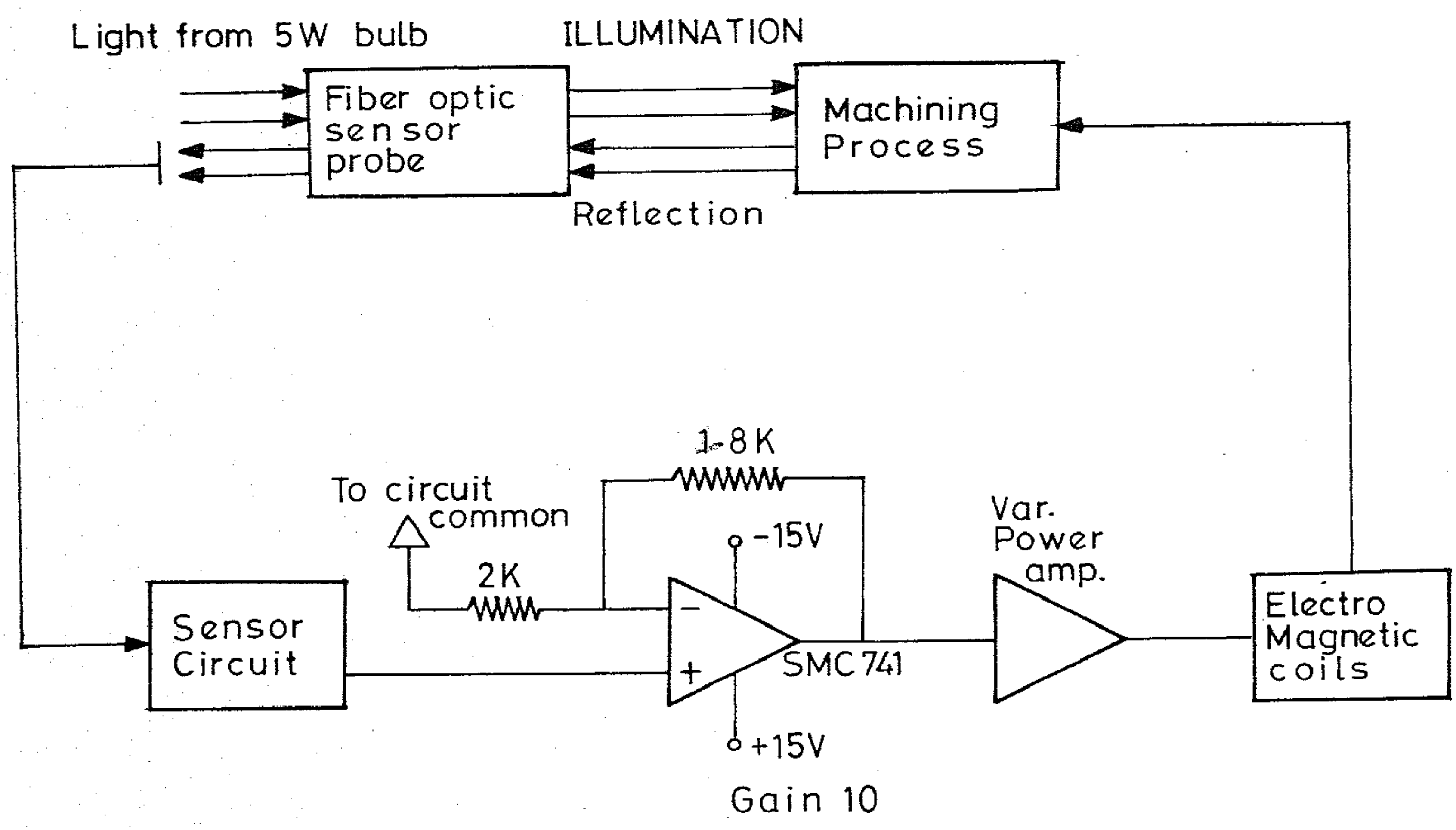


FIG.2·10 Feed back circuit

As stated earlier, the power amplification required, varies with cutting conditions. Since the sensitivity of the sensing circuit has already been calibrated the power amplification needed can be calculated with known input to the exciter. The amplification of the power amplifier for different sensitivities is given in Table 2.6.

In order to set, measure and record the signals in real time while machining, the following instruments are needed:

(i) Digital storage oscilloscope

(ii) Digital voltmeter

(iii) Recorder

For each and every cutting condition the initial DC component of the output signal from the sensing circuit (Fig. 2.3) has to be offset. As the sensor probe follows the tool; the sensor will sense vibrations with respect to machined surface. Hence initially the workpiece has to be machined for a particular length and then the DC component has to be offset. This can be done by the potentiometer included in the circuit. A digital voltmeter can be used for this purpose.

The recording of the signals from the differential amplifier is accomplished by a Hi-scribe recorder. The amplification can be checked with an oscilloscope.

An overall view of the set up is shown in Fig. 2.11.

Table 2.6 : Power Amplifier Amplification

Cutting conditions	Sensitivity of the sensor mV/μm	Amplification
1	0.765	48
2	2.026	18.2
3	2.206	16.6
4	1.157	31.8
5	1.532	24
7	1.682	21.8
8	1.068	34.4
9	1.043	35.24

$$\text{Amplification} = \frac{\text{Excitation voltage (R.M.S.)/p-p amp. } \mu\text{m} \times 1.414}{10 \text{ 's' } \times 10^{-3}}$$

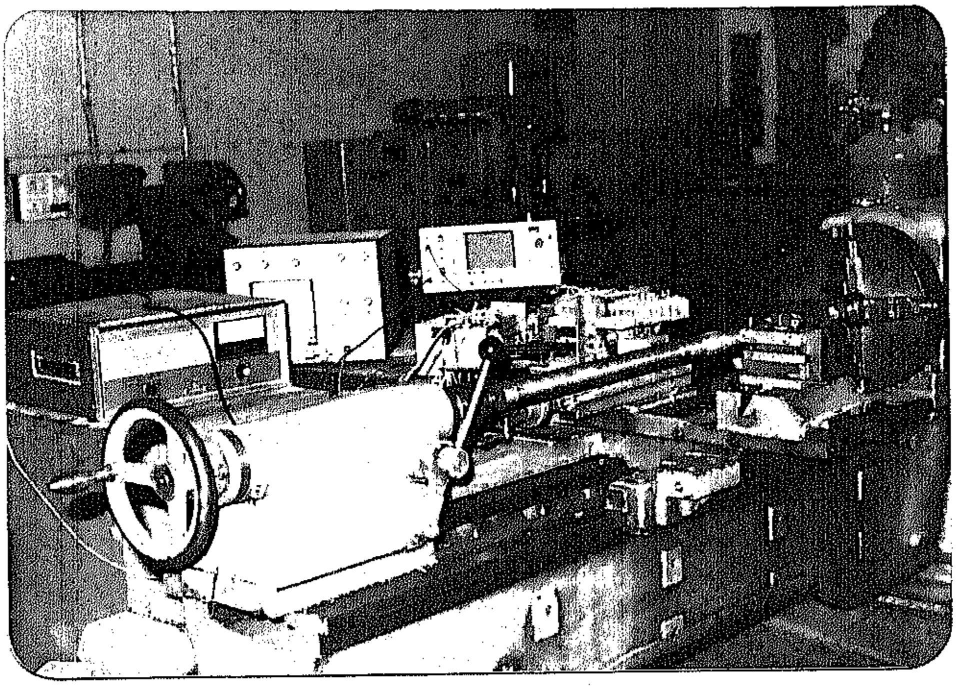


Fig. 2.11 . An overall view of set-up.

Chapter 3

Experimental Results and Discussion

A series of experiments was conducted to determine the performance of the control system. Experiments were conducted for the first seven cutting conditions listed out in Table 2.1. Experiment was also conducted for cutting speed of 37.82 m/min; feed 0.05 mm/rev. and a depth of cut of 0.4 mm.

The workpiece was clamped in a four jaw chuck and supported at the tailstock end by a revolving centre. The workpiece was first rough turned by a rear tool post. This operation was necessary to remove the ovality of the workpiece. This rough-turned workpiece was then turned with the tool which is fixed in the vibrator cum tool holder. Since the set-up is designed basically for finishing operations, small values of depth of cut is taken for turning. The depth of cut was set by a dial gauge.

As the probe lags the tool by a certain distance, for initial setting of the signal voltage level, the workpiece was turned up to a certain length. Then after interrupting the machining process, the output signal from the sensing circuit (Fig. 2.3) was set to zero by the potentiometer. Then the job was turned up to a certain length without feedback, then the feedback signal was fed through the power amplifier. The amplification was set according to the calculated values given in Table 2.7. The signals from the sensing circuit were recorded in a Hi-scribe recorder.

The output signals from the sensing circuit without feedback and with feedback are shown in Figs. 3.1 to 3.8. Graphs representing surface profile measured by the Taylor Hobson Talysurf are also shown in Figs. 3.1 to 3.8. The average roughness (R_a) value for the entire cutting length was also measured by the Talysurf. The values of average surface roughness for all cutting conditions with which experiments were conducted both with and without feedback are given in Table 3.1.

3.2 Discussion of Results

From the average surface roughness values (Table 3.1) it is seen that the surface finish has improved for all the cutting conditions when the feedback signal was introduced. In addition, it is also observed that the waveform pattern of the signals from the sensing circuit has slowly decayed to a stable signal after the feedback signal was passed. This is also clear from Talysurf measurements.

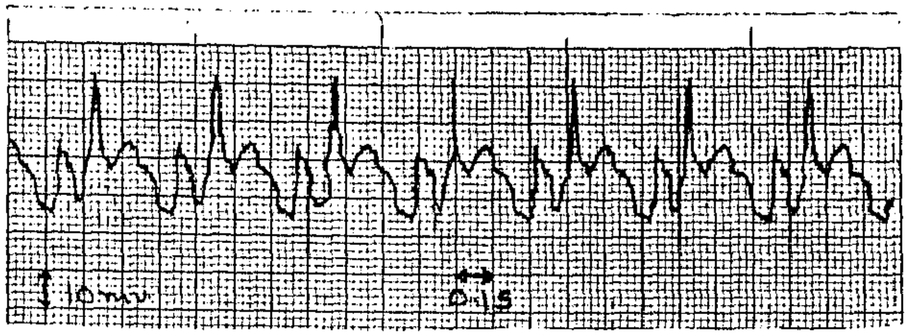
The improvement in surface finish has varied for different cutting conditions. This improvement in surface finish can be expressed by a socalled "improvement coefficient" which can be defined as

$$\text{Improvement coefficient} = \frac{\text{Surface roughness without feedback} - \text{Surface roughness with feedback}}{\text{Surface roughness without feedback}} \qquad (3.1)$$

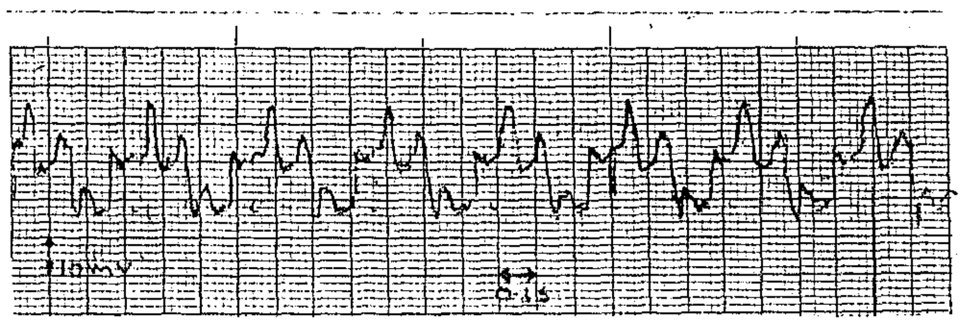
Table 3.1 : Experimental Results

Expt. No.	Cutting speed (m/min)	Feed mm/rev	Depth of cut mms	Surface roughness (μms)		Improvement coefficient
				Without feedback	With feedback	
1	24.20	0.05	0.3	20.0	17.0	0.15
2	24.20	0.075	0.3	12.0	10.0	0.166
3	24.20	0.10	0.3	11.5	10.0	0.13
4	30.25	0.050	0.3	18.0	14.0	0.22
5	30.25	0.075	0.3	18.5	15.0	0.18
6	30.25	0.10	0.3	19.1	15.0	0.215
7	38.72	0.05	0.3	13.0	12.1	0.070
8	38.72	0.05	0.4	14.5	14.1	0.027

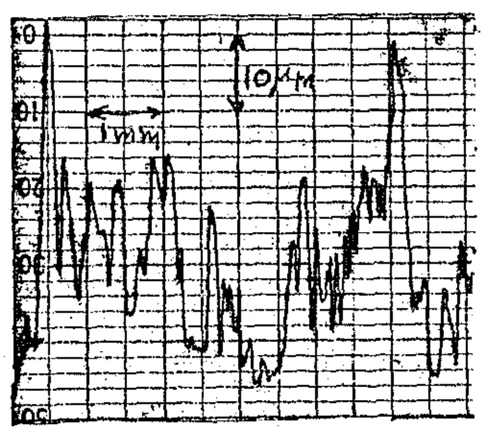
Workpiece diameter = 38.52 mms.



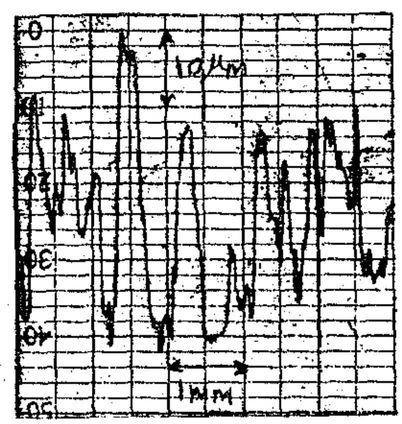
(a) Sensor signal pattern without feedback



(b) Sensor signal pattern with feedback

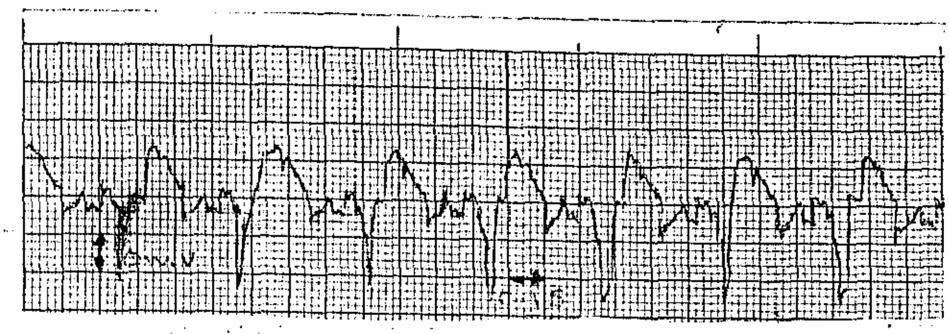


(c) Workpiece surface profile without feedback

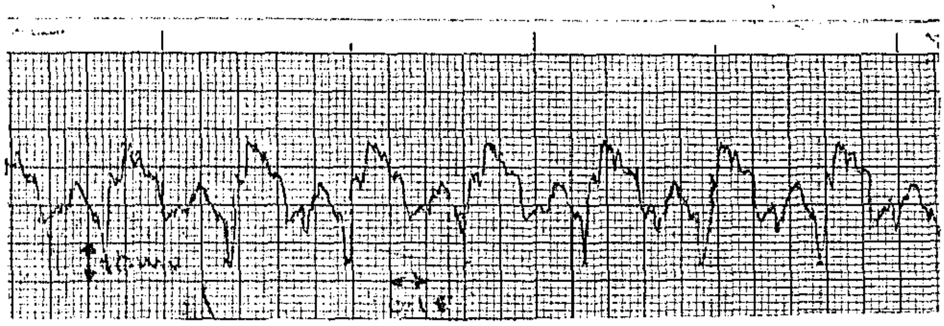


(d) Workpiece surface profile with feedback

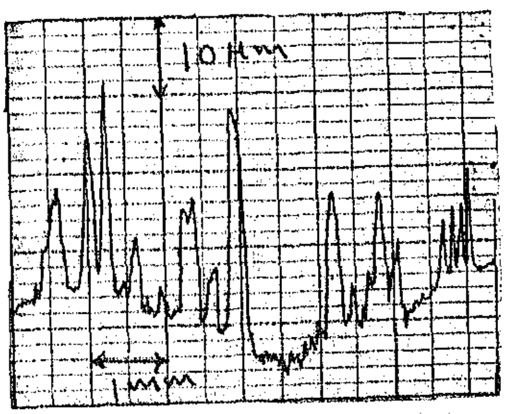
Fig. 3.1 : Recorded signals and surface profiles for experiment No.1.



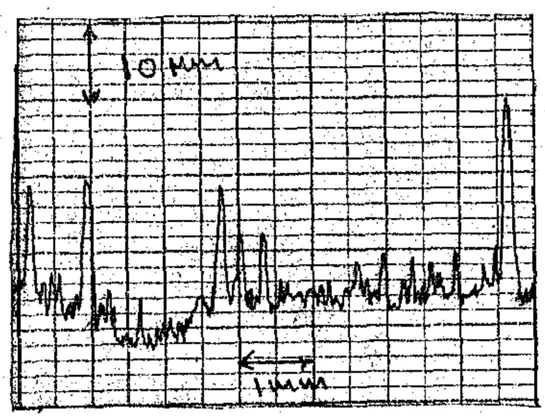
(a) Sensor signal pattern without feedback



(b) Sensor signal pattern with feedback

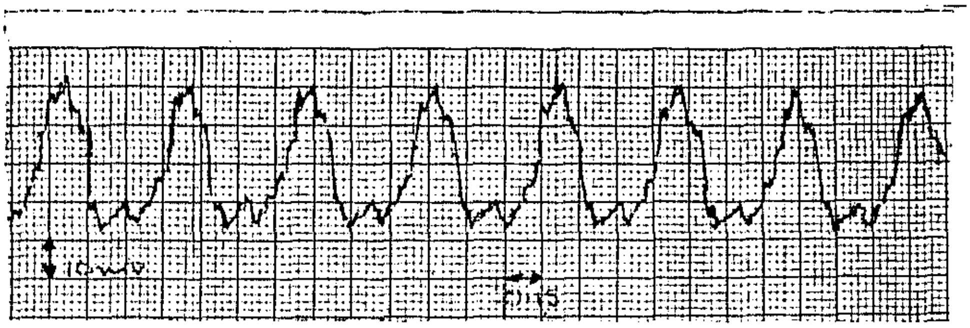


(c) Workpiece surface profile without feedback

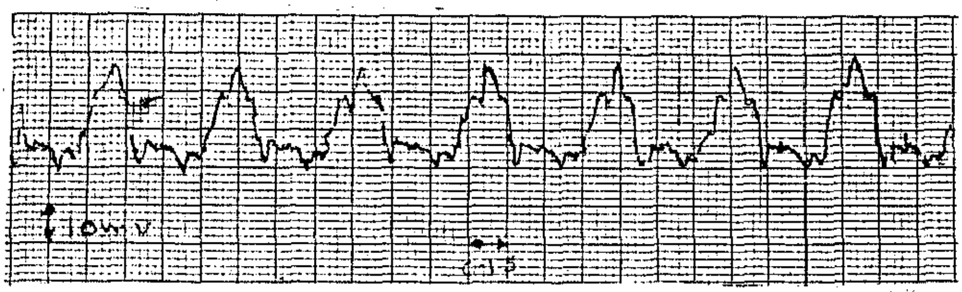


(d) Workpiece surface profile with feedback

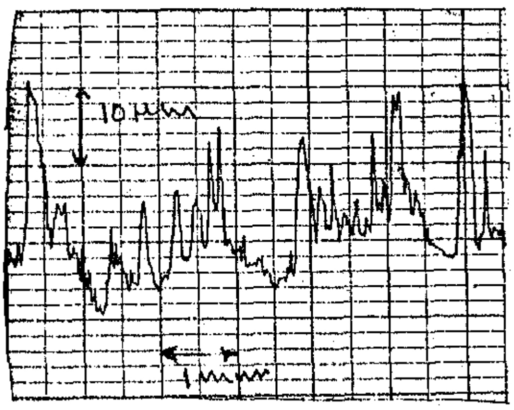
Fig.3.2 : Recorded signals and surface profiles for experiment no.2.



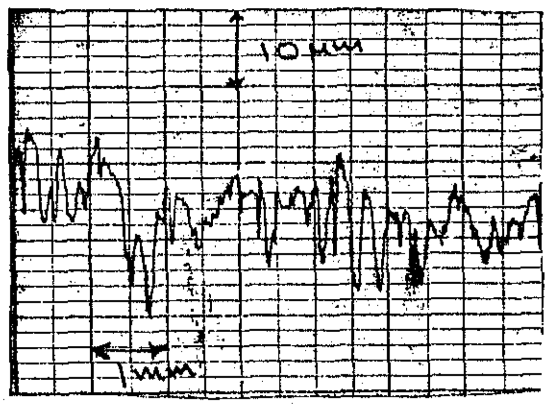
(a) Sensor signal pattern without feedback



(b) Sensor signal pattern with feedback

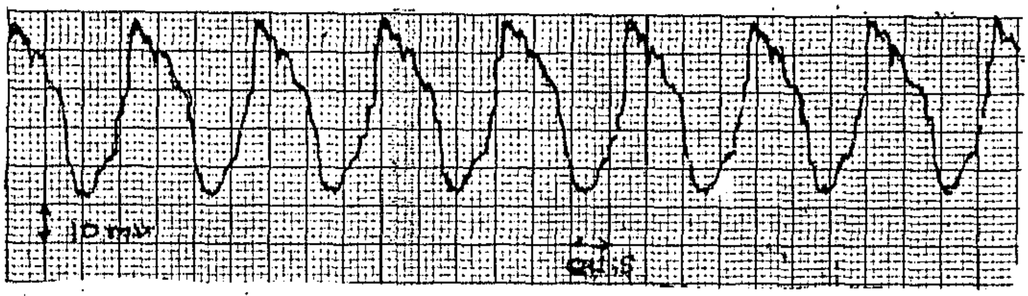


(c) Workpiece surface profile without feedback

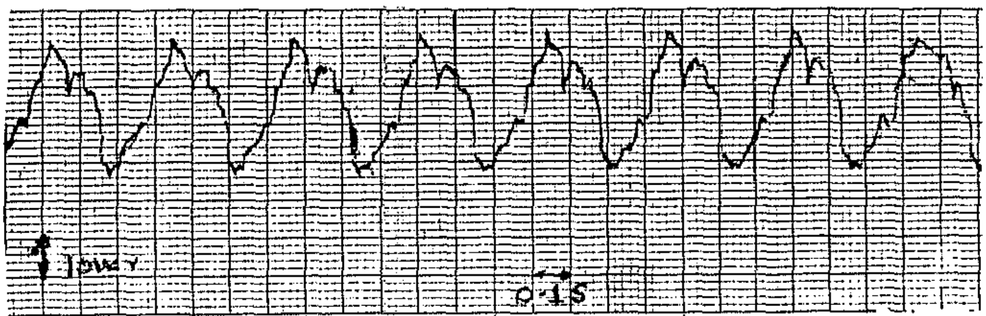


(d) Workpiece surface profile with feedback

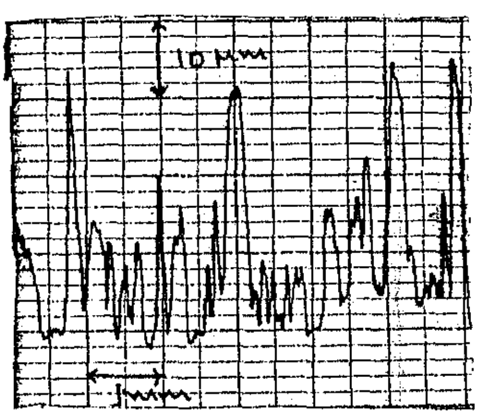
Fig. 3.3 : Recorded signals and surface profiles for experiment no.3.



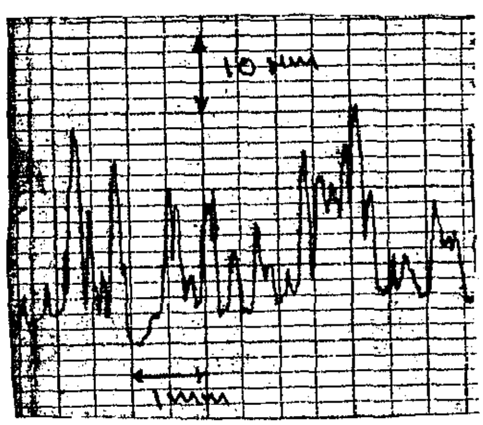
(a) Sensor signal pattern with out feedback



(b) Sensor signal pattern with feedback

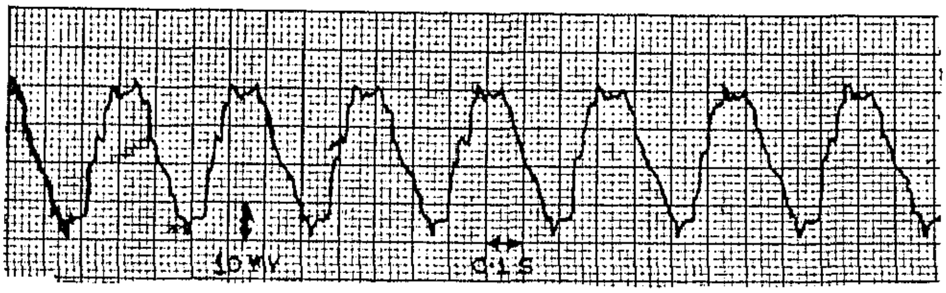


(c) Workpiece surface profile with out feedback

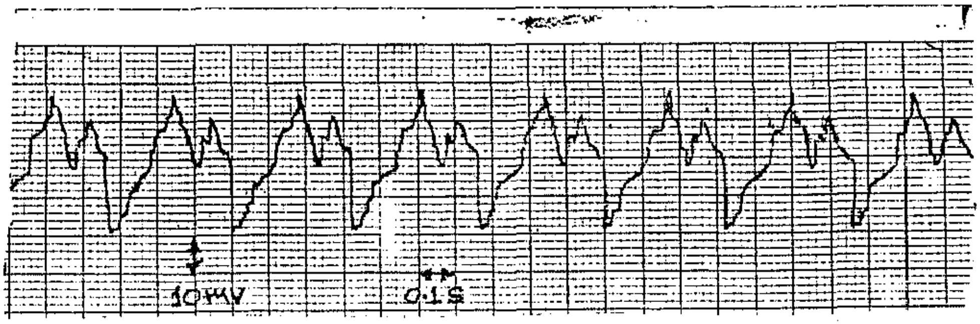


(d) Workpiece surface profile with feedback

Fig.3.4 : Recorded signals and surface profiles for experiment no.4.

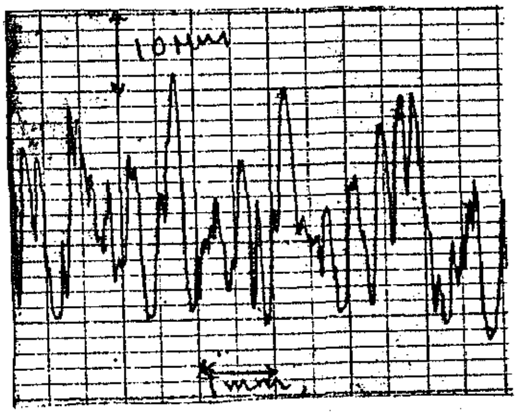


(a) Sensor signal pattern without feedback



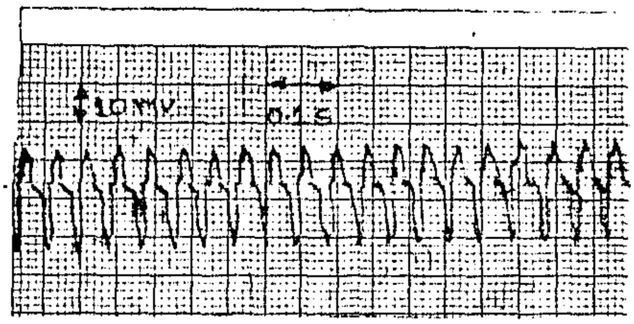
(b) Sensor signal pattern with feedback

(c) Workpiece surface profile without feedback

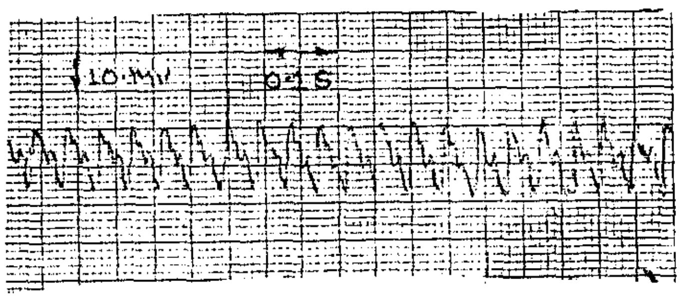


(d) Workpiece surface profile with feedback

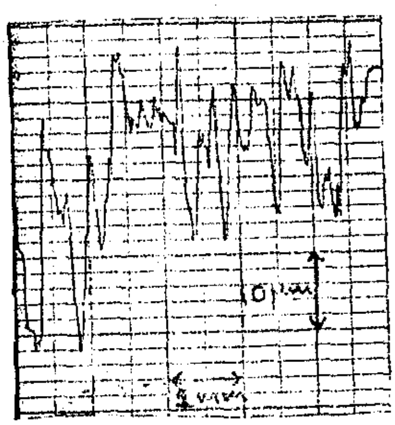
Fig. 3.5: Recorded signals and surface profiles for experiment no.5.



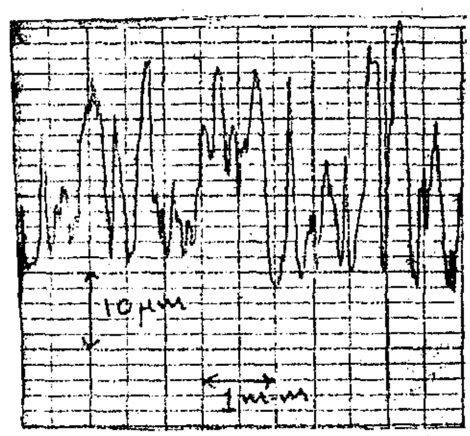
(a) Sensor signal pattern without feedback



(b) Sensor signal pattern with feedback

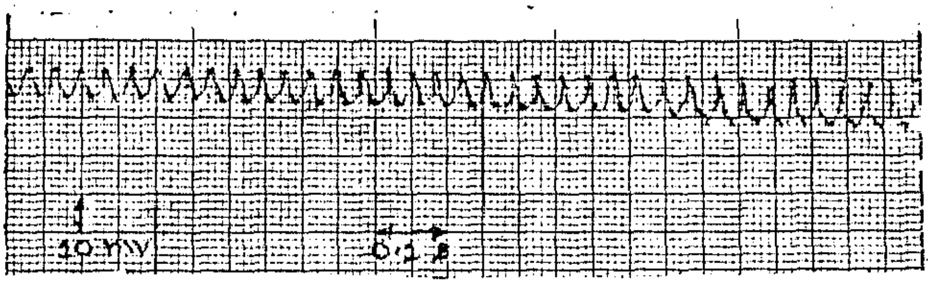


(c) Workpiece surface profile without feedback

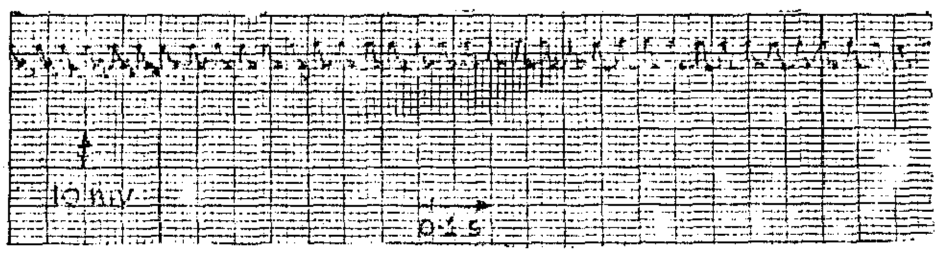


(d) Workpiece surface profile with feedback

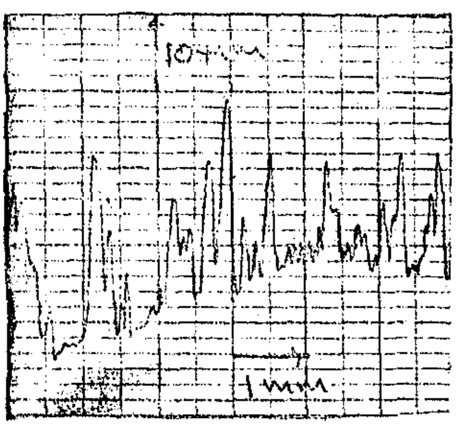
Fig. 3.6 : Recorded signals and surface profiles for experiment no.6.



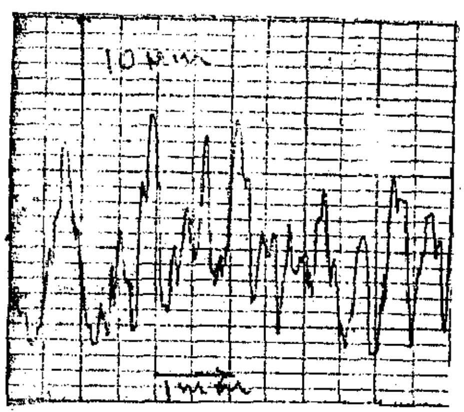
(a) Sensor signal pattern without feedback



(b) Sensor signal pattern with feedback

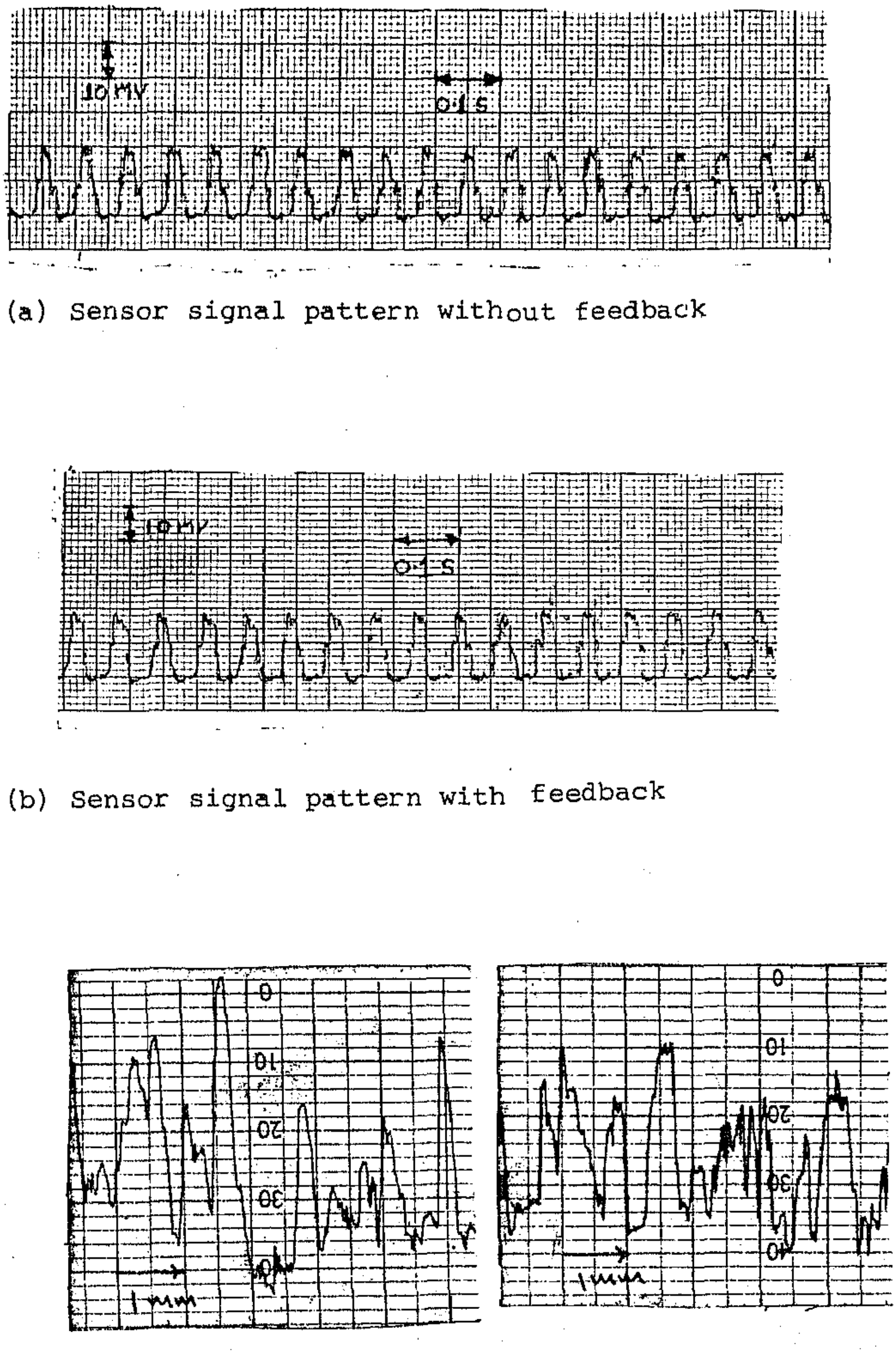


(c) Workpiece surface profile without feedback



(d) Workpiece surface profile with feedback

Fig.3.7 : Recorded signals and surface profiles for experiment no. 7.



(a) Sensor signal pattern without feedback

(b) Sensor signal pattern with feedback

(c) Workpiece surface profile without feedback

(d) Workpiece surface profile with feedback

Fig. 3.8 : Recorded signals and surface profiles for experiment no. 8.

The values of improvement coefficient for different cutting conditions are given in Table 3.1. The values show a reasonable improvement for all the experiments. The improvement coefficient is in the range of 0.024 to 0.22.

This improvement in surface finish is also seen from the signals recorded from the sensing circuit without and with feedback. There is a distinct reduction in the amplitude of the signals with feedback as compared to the signals without feedback. This amplitude reduction can be defined by a parameter "Amplitude Reduction Ratio" (ARR). This parameter can be defined as

$$\text{ARR} = \frac{\text{Peak-to-peak amplitude of vibration without feedback } (A)}{\text{Peak-to-peak amplitude of vibration with feedback } (A_F)} \tag{3.2}$$

As the sensitivity of the sensor is already determined (Table 2.3), the vibration amplitude can be calculated as

$$\text{Peak-to-peak amplitude } (\mu\text{m}) = \frac{\text{Peak-to-peak voltage}}{\text{sensitivity 's'}} \tag{3.3}$$

The calculated values of ARR and peak-to-peak amplitude have been tabulated in Table 3.2. For an effective control system the ARR should be greater than 1. The ARR has varied from 1.05 to 1.33. The ARR is less for a higher depth of cut as seen from Experiment No. 8.

Table 3.2 : Amplitude Reduction Ratios for Various Experiments

Expt. No.	Peak-to peak voltage (mV)		Peak-to-peak amplitude (μ ms)		ARR
	Without feedback	With feedback	Without feedback (A)	With feedback (A_F)	
1	37	29	48.37	37.91	1.276
2	40	32	19.74	15.79	1.25
3	36	29	16.32	13.15	1.24
4	45	35	38.89	30.25	1.286
5	40	34	26.11	22.19	1.176
6	24	18	18.88	14.16	1.33
7	9	8	5.35	4.756	1.125
8	21	20	12.48	11.89	1.05

Chapter 4

Conclusion and Scope for Future Work

4.1 Conclusions

An on-line control system has been designed and tested experimentally. The main objective of improving surface finish has been fulfilled. The performance of the control system has been tested for a certain range of cutting conditions. The principle of the present work is to reduce the disturbing force by an equal and opposite disturbing force.

The following design objectives have been fulfilled:

(i) Designing an accurate, reliable and sensitive sensor for sensing vibrations in real time.

(ii) Design, fabrication and testing of an exciter-cum-tool holder to excite the tool.

(iii) Design of a feedback system to control the Chatter occurring during turning operation.

The control system is capable of controlling the Chatter mode within a wide range of frequencies. An additional advantage of the control system is ease of sensing relative displacements because of sufficiently wide range of linearity. As there is no variation between the dynamic

and static sensitivities of the sensor, determining the response of the sensor for any surface can be accomplished by means of static calibration which is easier than that of dynamic calibration. Calibration results also indicate that the sensitivity of the sensor increases with better surface finish.

A principal advantage of the control system is the simplicity of the instrumentation. Instead of the conventional laser beam used in optical sensors an ordinary bulb was used for illumination of the workpiece surface.

However the introduction of an elastic element in the system will lead to a certain amount of instability. The demonstrated results hold good for finishing operations only. Another drawback of the system is that a self adaptive controller is not included in the system. The control is being done manually.

4.2 Scope for Future Work

The present work can be extended further. The system is designed for a single-input and single-output (i.e. the system responds to the principal Chatter mode at a time.) The system can also be designed to respond to other principal modes. A self adaptive controller can be included in the system to control the performance of the system under all conditions. The transportation lag in the sensor can also be taken care of by the controller. This lag can also be reduced

by positioning the sensor probe directly opposite to the tool tip in the radial direction.

The principle of control can also be extended to other machine tools such as grinding, milling, etc.

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Appendix - I

Machine-tool Chatter Theory

The machining of metals is often accompanied by a violent relative vibration between work and tool which is called Chatter. The conventional theory of metal cutting deals entirely with the steady-state cutting process in which the cutting takes place under vibration-free conditions. Under steady-state conditions, the chip-thickness, chip width and the cutting speed remain constant.

Let it be assumed that the cutting tool strikes a hard inclusion in the workpiece material and that as a result the forces acting on the tool increases by a small amount. The initial force, however, has already been absorbed by the static deformation of the machine-tool structure. The increase in the forces gives rise to further deformation. Furthermore, the torque acting on the work is increased by a small amount, and this is absorbed by elastic torsional deformation in the drive, with the result that a drop in cutting speed takes place. If the hard inclusion breaks out at time $t = 0$, a sudden drop in cutting force and torque will occur, and consequently the potential energy stored in the machine-tool structure as the drive will be released to

arise vibration in the system. Similar conditions arise when an elastic system is given an impulse which leads to elastic deformation resulting in vibration. Steady-state cutting process will not be resumed until the vibration has decayed.

This means that it is possible for disturbance affecting the steady-state cutting process to create vibration in the machine tool. If the steady-state cutting operation is disturbed, an additional cutting force element dP will be generated, superimposed on the cutting force P. It may happen that dP is of such a form that it increases the original disturbance, so that a still larger dP is set up and this in turn leads to an even more severe disturbance, and so on. Consequently the machine begins to vibrate,the amplitudes of the vibration rising exponentially. Under these conditions the system is unstable. On the other hand, of course, dP may act in counter to the disturbance, so that the original disturbance vanishes and steady state cutting is resumed. Under these conditions the system is stable.

The disturbance affecting the cutting process is time dependent, and therefore the cutting-force element dP is also a function of time. (Now if a time-variable force acts on the machine tool the latter will be thrown into vibration). If Chatter occurs, however, the time dependence of dP will not alone give rise to instability. The important

property of dP is that it depends not only on the displacement brought about by the disturbance, but also on its velocity. Forces which are velocity dependent can be regarded as damping forces, and consequently they may be either added to or subtracted from the damping forces of the system. If the damping force introduced is in opposite phase with the disturbing force (usually friction between bolted joints) the result is that the prevailing disturbance will rapidly decay. On the other hand, if the damping force is in phase with the disturbing force, it will reduce the damping of the system. This means that energy is introduced to build up vibration and maintain it. The machine-tool drive acts as the energy reservoir for this purpose.

In lathe operations, one of the most important physical effects, which can lead to dynamic instability is the regenerative effect. The regenerative effect occurs with single-edged tools when the cutting edge cuts a work surface, having marks of previous passes.

Majority of investigations on the dynamic behaviour of Lathe show that under Chatter conditions one of the following vibratory systems is thrown into self-induced vibration: (1) spindle-workpiece or spindle-workpiece-tailstock, (2) workpiece, (3) tool.

Hence, in order to avoid Chatter, rigidity of the weakest element has to be increased.

Appendix - II

On-Line Control

On-line control of metal-cutting processes is a logical extension of the CNC systems. This on-line control is known as adaptive control. For a machining operation, the term "adaptive control" denotes a control system that measures certain output process variables and uses these to control the input process variables such as speed, feedrate and depth of cut. Nearly all the cutting parameters that can be measured during metal cutting have been controlled in experimental adaptive control systems. The motivation for developing an adaptive control system lies in trying to operate the process more efficiently. The typical performance indices have been metal removal rate and cost per unit volume of metal removed.

Adaptive control is basically a feedback system in which the operating parameters automatically adapt themselves to the actual conditions of the process. There are many causes for variability in machining where adaptive control can be applied and are listed as follows:

(i) Variable geometry of cut in the form of changing depth or width of cut. In these cases feed rate is

usually adjusted to compensate the variability.
Ex: Profile milling, contouring operations.

(ii) Variable workpiece hardness and variable machinability. When hard inclusions in other sorts of difficulties are encountered in the workpiece, either speed or feed is reduced to avoid premature failure of the tool.

(iii) Variable workpiece rigidity: If the workpiece deflects as a result of insufficient rigidity in the setup, the feedrate must be reduced to maintain accuracy of the process.

(iv) Tool wear: It has been observed that as tool begins to dull, cutting forces increase. An adaptive control system measures the amount of wear in terms of voltage and feeds it back to the cutting zone to move the tool towards the workpiece surface compensating the tool wear.

(v) Intermittent cutting: The workpiece geometry may contain shaped sections where no machining needs to be performed. The typical procedure is to increase feedrates when the gaps are encountered, to improve metal removal rate.

Adaptive control system for machine tools can be classified as (a) Adaptive Control Optimization (ACO), (b) Adaptive Control Constraint (ACC).

In ACO, an index of performance is specified for the system. This specified performance index is a measure of the overall process performance, such as production rate or cost per unit volume of metal removed. The process variables are usually considered to be feed and/or speed in the operation. Although there has been considerable research in the development of ACO systems, few, if any, of these systems are used in practice. The major problems with such systems have been difficulties in defining realistic indices of performance and the lack of suitable sensors which can perform on-line measurement of the necessary parameters in a production environment.

With ACC, the machining parameters are maximized within a prescribed region bounded by process and system constraints, such as maximum torque, power etc. Practically all the Adaptive Control systems for cutting processes which are used in the industries today are of the ACC type and seldom involve the control of more than one operating parameter.

The benefits of adaptive control of machining process are increased production rates, increased tool life, improved accuracy and surface finish, greater safety, less operator intervention and, therefore, less production cost.

Appendix - III

IIIa. The Power Amplifier

The completely transistorized power amplifiers included in the control system deliver full performance at high efficiency over the entire frequency range. Reduced distortion, noise and wider flat frequency response are the major benefits of the solid-state design. Over-current protection is incorporated in the driver-output stage to reduce the output current to a minimum level whenever the current exceeds a preset value.

IIIb. Power Amplifier Performance

Amplifier Model	2250 MB
Power output:	250 Va, 5-10,000 Hz
Frequency range:	5-20,000 Hz
Input Impedance:	10,000 Ohm
Frequency response at 1.0V input:	± 1 db 5-20,000 Hz
Distortion:	Less than 1%, 5-3,000 Hz. Less than 3% 5-20,000 Hz with output voltage derating linearly above 10,000 Hz
Hum and Noise:	75 db below full output
Signal Input Voltage:	Less than 10V rms for full output

Power Input:	110/220V, 600 Va, 50/60 Hz
Power Dissipation:	400W
Physical dimension:	
Portable Model:	17" wx6-3/4"hx14-3/4" d
Weight:	49 pounds

Appendix - IV

Specifications of The Lathe

Type of centre lathe	:	HMT LB 17
Centre height	:	170 mm.
Centre distance	:	1000 mm
Swing over bed	:	350 mm
Swing over cross slide	:	170 mm
Spindle speeds	:	18, 45 to 2000 RPM
		(10 HP/3000 RPM motor)

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